BULK COMPOSITION AND ^{40}AR-^{39}AR AGE DATING SUGGESTS IMPACT MELT SAMPLE 67095 MAY BE EXOTIC TO THE APOLLO 16 SITE.

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Introduction: Radiometric dating of the returned Apollo samples has shown a clustering of impact events ~4.0-3.8 Ga (e.g., [1]) that some have argued is due to a temporal increase in the bombardment frequency of the lunar surface, and of the inner solar system itself (e.g., [2]). We aim to constrain the bombardment history of the lunar highlands through examination of Apollo 16 impact melts >1.5 g, to test if these reflect a single impact event (e.g., Imbrium). Concurrently, other investigators are conducting similar analyses on smaller, cm-sized impact melt clasts within Apollo 16 breccias [3]. These studies will work in conjunction to better constrain the impact history of the Apollo 16 site in type of impactor, age of impacts, and the characterization of target materials. This work is part of a larger study encompassing the characterization of 17 individual samples from at least 5 compositional subgroups [4] using bulk composition, mineral phase chemistry, Ar-Ar age dating, and highly-siderophile element compositions. However, this abstract focuses on two samples, 60635 and 67095, whose Ar-Ar ages have recently been determined.

Sample Descriptions and Geologic Context:

60635: This is a coarse-grained, subophitic impact melt with a network of interconnected plagioclase laths (~69 %) and pyroxene (~11 %; [5]). Large plagioclase laths and prisms (0.5 to 2 mm) dominate the sample; smaller plagioclase laths (~200 μm) and pyroxene crystals (~100 to 200 μm) are confined to angular interstices. Olivine is absent, but traces of ulvöspinel, troilite, and K-feldspar have been identified [6].

67095: Sample 67095 is a subophitic impact melt composed of ~62% plagioclase, ~17% orthopyroxene and ~12% olivine [7]. Plagioclase laths (90-900 μm) and blocky crystals (400 μm-1.5 mm) dominate the sample while subophitically enclosing pyroxene and olivine. Some subhedral olivine crystals (150 μm to 1.2 mm) are partially rimmed by pyroxene. Ilmenite is a minor phase found as laths (60 to 600 μm).

Context: 60635 (15 g) was collected as a rake sample ~72 m SW of the Lunar Module outside of a very subdued crater (180 m diameter) on the Cayley Plains [8]. It has been suggested that 60635 may represent ejecta from South Ray Crater, as distal ejecta has been shown to extend to the Lunar Module site [9]. 67095 (340g) was collected inside the E-SE rim crest of North Ray Crater, ~120 m S-SW of House Rock [10]. It was collected because of its black glass coat and may be associated with a secondary crater (1m diameter) on the North Ray Crater rim [10].

Methods: Each sample was characterized using adjoining sample aliquots from a texturally homogeneous area of the parent sample. The subsample splits and analyses performed on the splits are listed in Table 1.

Table 1. Subsample Number and Type.

Sample	Bulk Composition	^{40}Ar-^{39}Ar Ages
60635	,19	,20
67095	,122	,124

Bulk composition. 50-mg aliquots were ground with an agate mortar and pestle and then digested in ultrapure HF and HNO_3 (2:1 ratio) before being brought to a final volume of ~100 g in 5% HNO_3 with dilution factors of ~2000. Major element analyses of the whole-rock composition of the samples were performed at the Center for Environmental Science and Technology (CEST) using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). Trace element determinations were conducted at the Midwest Isotope and Trace Element Research and Analysis Center (MITERAC) using ICP-MS. Both facilities are housed at the University of Notre Dame. Procedural blanks and four terrestrial basaltic standard reference materials and were analyzed as unknowns along with the impact melt samples following the method of [11].

^{40}Ar-^{39}Ar Age Determination. Two to three splits (~10 mg each) of each sample were irradiated at the Cd-Lined In-Core Irradiation Tube (CLICIT) facility at Oregon State University; PP-20 Hb3gr Hornblende GSC was the primary irradiation monitor to determine the J-factor. Argon was extracted from each sample using a computer controlled double-vacuum resistance-heated furnace. Typical temperature steps were from 300 to 1500 °C in 50 °C intervals, totaling 25 heating steps per split. The released gas was purified and then analyzed in a VG 5400 mass spectrometer. Uncertainties and corrections were applied to account for blanks, mass-dependent discrimination, spallation-produced isotopes, and interfering isotopes produced in the reactor from Ca and K. Isochron techniques were applied to determine the ratio of reimplanted lunar ^{40}Ar to implanted solar wind ^{36}Ar and appropriate corrections were made. When the ratio could not be reliably determined, a value of 8±8 was applied, to encompass values expected in lunar breccias [12].

Results: *Bulk composition.* Samples 60635 and 67095 belong to separate compositional groups. Sample 60635 is characterized as a member of Group 3 based on its Sm-Sc content by [4]. 67095 is classified as a Group 2M impact melt, a mafic (M) member of Group 2, which has higher Sm, but similar Sc abundances to Group 3 impact melts. Both samples exhibit chondrite-normalized profiles with negative Eu, Ta, Sr, and Y anomalies (Fig. 1). In addition, both are relatively enriched in the incompatible trace elements (ITE) in comparison to other members from their respective groups. Finally, although 60635 has a broadly similar major element composition to the Apollo 16 soils, 67095 is significantly more mafic (Fig. 2).

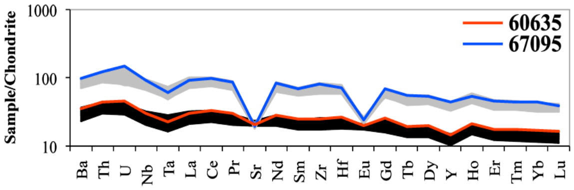

Fig 1. Chondrite-normalized [13] ITE bulk analyses in order of increasing compatibility (right to left). Abundances for selected Group 2M and Group 3 samples are shown in grey- and black-shaded regions, respectively.

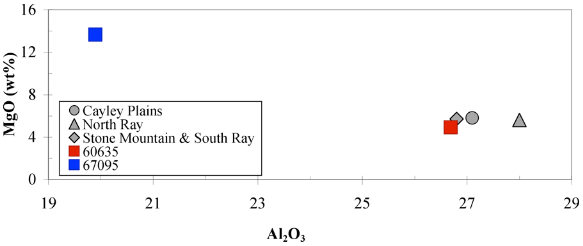

Fig 2. Selected major element abundances of 60635 and 67095 in conjunction with average soil abundances from three geographic areas of the Apollo 16 site [14].

^{40}Ar-^{39}Ar Ages. Preliminary Ar-Ar analyses of 60635 indicate that it formed, or was completely reset, at ~3880±20 Ma with no more than minor thermal disturbances at later dates. This is in general agreement with Rb-Sr analyses from [5]. Analyses of 67095 suggest that the sample has been substantially degassed in the last 700 Ma with an apparent age spectrum typical of the diffusion profile expected. The oldest apparent age for 67095 (i.e., the formation age lower limit) is ~3900 Ma. While formation ages could potentially be older, all three splits are in broad agreement for the oldest apparent age, though some variability exists on the younger apparent ages. There is evidence of a recent thermal event causing loss of 35-55% of the radiogenic ^{40}Ar in the different splits. Both 60635 and 67095 are consistent with being produced during the era of basin-forming events. While the lower limit for formation age of 67095 is indistinguishable from the age of 60635, it is important to emphasize that the former is only a lower limit. Hence, it is not clear whether the two formed in the same event or two distinct events. This is the first reported age for 67095.

Discussion and Implications: The bulk compositions of the two samples are not unique among their respective groups, though each is one of the most enriched members (Fig. 1). The negative Eu anomaly in both bulk rock samples is surprising considering the plagioclase-rich nature of these samples and suggests (1) the bulk target material contained a net negative Eu anomaly, or (2) there was significant fractionation of plagioclase. The Sr anomalies in both samples are also suggestive of plagioclase fractionation or a parental melt relatively depleted in Sr. However, given the relatively Al_2O_3-rich nature of these impact melts (Fig. 2), the target material would be rich in plagioclase, thus negating the second option. Sample 60635 is less enriched than 67095 in nearly all of the ITEs, which may indicate different target materials for each of these samples, suggesting they formed from different impact events. Moreover, given the distinct chemistry of 67095 compared to average Apollo 16 soils, it is plausible that 67095 is exotic to the site; in contrast, the major element chemistry of 60635 is broadly similar to that of the Apollo 16 soils suggesting that it formed from local materials. Sample 67095 also shows evidence of a significant thermal event at 700 Ma or more recently, plausibly the impact that launched it to the Apollo 16 site. Thus, the age and bulk composition of these two samples agree with the findings of [15] suggesting the impact melt samples reflect the influence of several impacts at the Apollo 16 site.

References: [1] Tera F. et al. (1974) *EPSL*, **22**, 1-21. [2] Kring D.A. and Cohen B.A. (2002) *JGR*, **107**, E2, 5009. [3] Niihara T. et al. (2013) *GCA*, submitted. [4] Korotev R.L. (1994) *GCA*, **58**, 3931-3969. [5] Deutsch A. and Stöffler D. (1987) *GCA*, **51**, 1951-1964. [6] Dowty E. et al. (1974) *5th Proc. LSC*, 431-445. [7] Warren P.H. and Wasson J.T. (1978) *9th Proc. LPSC*, 185-217. [8] Schaber G.G. (1981) In *Geology of the Apollo 16 Area, Central Lunar Highlands*, *USGS Prof. Paper. 1048*, 21-44. [9] Sutton R.L. (1981) In *Geology of the Apollo 16 Area, Central Lunar Highlands*, *USGS Prof. Paper. 1048*, 231-525. [10] Ulrich G.E. (1981) In *Geology of the Apollo 16 Area, Central Lunar Highlands*, *USGS Prof. Paper. 1048*, 45-81. [11] Neal C.R. (2001) *JGR*, **106**, E11, 27865-27885. [12] Eugster O. et al. (2001) *MaPS* 36, 1097-1115. [13] Anders E. and Grevesse N. (1989) *GCA*, **53**, 197-214. [14] McKay et al. (1981) In *Lunar Sourcebook*, 285-356. [15] Norman M.D. et al. (2006) *GCA*, **70**, 6032-6049.