APOLLO 17 LUNAR IMPACT GLASSES: AGES EVALUATED VIA STATISTICAL AND COMPOSITIONAL STUDIES N. E. B. Zellner[1], P. Q. Nguyen[2], T. D. Swindle[3], S. Beard[3], and C. Isachsen[3], [1]Department of Physics, Albion College, Albion, MI USA 49224, [2]Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48823, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ USA 85721.

Introduction: The unique composition of the Taurus-Littrow landing site and the diverse sample suite allow for studies of lunar geological processes. In particular, lunar impact glasses can provide evidence for impacts over the course of the Moon's history. In this study, we report on the major-element compositions of 114 lunar impact glasses from Apollo 17 regolith sample 71501,252 (5 g) and $^{40}Ar/^{39}Ar$ ages for a subset. In general, the distribution of lunar impact glass ages follows that of earlier reports [e.g., 1], including glasses with ages ~800 Ma [2] and ~3740 Ma [3].

Analyses: We have previously reported on a set of 13 lunar impact glasses from the Apollo 17 regolith 71501,252 [4]. Within the >125-micron fraction, 119 homogeneous and inclusion-free spherules and fragments of glass were handpicked with the aid of a binocular microscope then analyzed by electron microprobe. Of these, 114 were determined to be of impact origin and glasses with interesting compositions and high-K abundances were selected for isotopic dating by the laser step-heating $^{40}Ar/^{39}Ar$ method [1, 4]. To this data set, we add five new $^{40}Ar/^{39}Ar$ ages (Table 1). Age data for these impact glasses were assessed as "good", fair" or "poor" [1], following the guidelines of Jourdan (2012). Additionally, compositions of the impact glasses were compared to compositions of local Apollo 17 regoliths; glasses were then broadly characterized as "local" or "exotic" to the collection area [3].

Discussion: In general, the distribution of compositions of lunar impact glasses from 71501,252 is constrained to the local regolith composition (Figure 1), and spheres are most likely to reflect the "local" regolith composition, while shards do not. However, there is a wide spread in compositions, as expected at this site [4]. A glass' size and composition were evaluated against the quality of its $^{40}Ar/^{39}Ar$ age. As a result, glasses with sizes ≤200 μm and lowest Ar-retentivity as indicated by their low X(NBO) [i.e., non-bridging oxygens; 1, 5, 6] were most commonly found to yield $^{40}Ar/^{39}Ar$ ages with the highest uncertainties and the lowest-quality age plot (i.e., "fair" or "poor"), though there are some exceptions (Table 1).

Statistical Study: In order to evaluate how likely it is that compositionally diverse glasses with the same $^{40}Ar/^{39}Ar$ age provide evidence for a global increase in impact flux, especially at ~800 Ma [2], principal component analysis (PCA) and a k-nearest neighbor algorithm were implemented. PCA is a useful method for reducing complex multidimensional data sets while still maintaining the variability found in the data. This analysis takes a set of features, in this case the chemical composition of the glasses, and performs an orthogonal transformation so that the data can be plotted on axes (i.e., principal components) that maximize the amount of variance. The k-nearest neighbor algorithm is trained with a set of data that is placed into predefined classes. When a new point of unclassified datum (i.e., glass composition) is introduced, the algorithm will decide which class (i.e., regolith composition) it belongs to, based on a majority vote of the nearest neighbors. Plotted results thus differentiate among glasses grouped with the regolith in which they were collected ("local") versus those that were grouped with a regolith sample from a different Apollo site ("exotic").

Compositional Study: Lunar impact glasses with ages ~3740 Ma have been observed in regolith samples from the Apollo 16 [3] and Apollo 15 [7] landing sites. One glass from 71501, sample #293 (3740 ± 50 Ma), has a similar well-defined age. To determine if these glasses originated in different compositional units, a plot of their major element ratios, CaO/Al_2O_3 versus MgO/Al_2O_3, was made [e.g., 8].

Results: Samples with ages of ~800 Ma [1, 2], including #311 (774 ± 114 Ma, [1, 4]), were evaluated as either "local" or "exotic" based on the nearest regolith sample next to which they were located (k = 1) on a plot of the first two principal components of the PCA. The composition of sample #311 was found to most closely match the Apollo 12 regolith, and thus is "exotic" to the Apollo 17 site. Taken together with glasses of similar age reported in previous studies [1, 2], a global impact event is supported. An evaluation of whether or not this sample came from Copernicus [e.g., 10] will be presented.

Figure 2 shows a plot of the major-element ratios of five lunar impact glasses with $^{40}Ar/^{39}Ar$ ages of ~3740 Ma. The Apollo 16 impact glasses were previously demonstrated [3] to represent a single impact event; two additional impact glasses from two different regolith samples also possess this well-defined age. Together, these three sets of glasses provide evidence for an enhanced impact flux ~3740 Ma. Along with Apollo 17 (Table 1) and other [1] lunar impact glasses with ages >3500 Ma, a protracted late heavy bombardment is supported [e.g., 1, 9, 11, 12]. Statistical data, including an assessment of areas in which these impact glasses may have formed, will be presented.

Conclusion: Impact glasses from regolith sample 71501,252 represent the compositional diversity of the Apollo 17 landing site. With a wide range of ages, these impact glasses [1, 4, and herein] provide evidence for the constant bombardment of the Moon. Apollo 17 impact glasses with ages ~800 Ma, >3500 Ma, and ~3740 Ma, similar to ages of impact glasses from other Apollo regoliths, provide evidence for increased global lunar bombardment at these times in particular.

Individual lunar impact glass ages can provide important information about the timing of the Moon's impact flux. However, impact glass ages are best evaluated by considering the glass' physical characteristics (i.e., shape, size, composition). Additionally, in order to assess whether or not lunar impact glasses represent global or local impacts, their data should be interpreted along with that of lunar impact glasses from other sites.

References: [1] Zellner N. E. B. and Delano J. W. (2015) *GCA* **161**, 203-218. [2] Zellner N. E. B. *et al.* (2009) *GCA*, **73**, 4590-4597. [3] Delano *et al.* (2007) *MAPS*, **42**, 993-1004. [4] Zellner *et al.* (2009) *MAPS*, **44**, 839-852. [5] Mysen B. O. and Richet P. (2005) Silicate Glasses and Melts: Properties and Structure. Elsevier, Amsterdam. 560pp. [6] Lee S. K. (2011) *PNAS* **108**, 6847-6852. [7] Zellner N. E. B. *et al.* (2013) 44th LPSC, Abstract #2539. [8] Zeigler *et al.* (2006) *GCA* **70**, 6050-6067. [9] Zellner N. E. B. (2017) *OLEB*, **47**, 261-280. [10] Bogard D. D. *et al.* (1994) *GCA*, **58**, 3093-3100. [11] Morbidelli A. *et al.* (2012) *EPSL*, **355-356**, 144-151. [12] Bottke W. F. *et al.* (2012) *Nature*, **458**, 78-81.

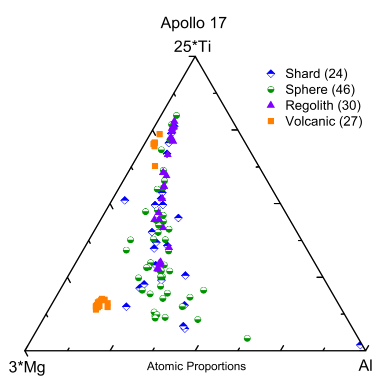

Figure 1. Atomic proportions of non-volatile lithophile elements for Apollo 17 glasses from 71501,262 [1, 4]. Regolith samples are from Simkin *et al*. 1973, Rose *et al.* 1973, 1975, Haskin *et al.* 1973, Wanke *et al.* 1973, Taylor *et al.* 1973, Gast *et al.* 1973a,b, Korotev 1981, Wanke *et al.* 1975, Hubbard *et al.* 1973, and Compston *et al.* 1973.

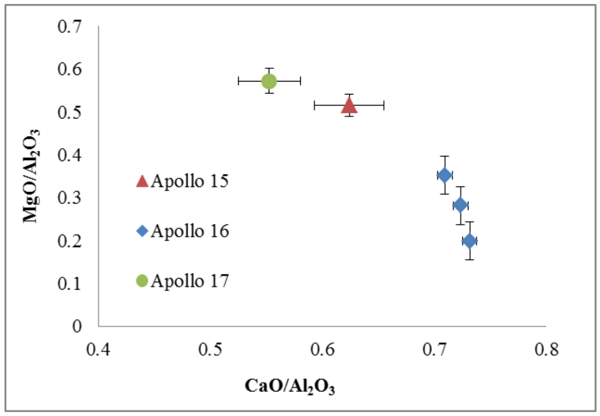

Figure 2. Glasses from the Apollo 15 [7], 16 [3], and 17 landing sites that yielded a well-defined $^{40}Ar/^{39}Ar$ age of ~3740 Ma.

Table 1. Shape, size, composition, and age data for select impact glasses from 71501,252, including five new ones. ND means no age was determined.

Sample	Shape Size (μm)	X(NBO)	$^{40}Ar/^{39}Ar$ Age (Ma) (assessment)	Ref.
289	sphere 200	0.34	1323 ± 904 (fair)	
293	shard 287	0.27	3740 ± 50 (good)	4
311	sphere 188	0.46	774 ± 114 (good)	1,4
369	shard good	0.38	3630 ± 40 (good)	1,4
375	shard 250	0.26	3475 ± 452 (fair)	
379	shard 135	0.38	ND (poor)	
383	shard 86	0.21	2533 ± 632 (fair)	
390	shard 135	0.25	3580 ± 45 (good)	4
393	shard 100	0.29	3316 ± 1198 (fair)	