

Introduction: Lunar impact glasses can reveal important compositional and temporal information about the evolution of the lunar crust and timing of the Moon's impact flux. These glasses are abundant in the lunar regolith and have compositions that are distinct from those of volcanic glasses. Additionally, because their compositions span the range of regolith compositions observed by lunar orbiting spacecraft, they provide information about areas not sampled by Apollo or Luna missions. A summary of past and current lunar impact glass investigations, using glasses from the Apollo 11, 12, 14, 15, 16, and 17 regoliths will be presented.

Early Sample Return Studies: Initial studies of the material in the lunar fines reported that impact glasses have a variety of distinct characteristics indicative of impact formation [e.g., 1,2], including flow features and/or shapes representative of rapid fusion and quenching (Figure 1) and/or a coating of impact-induced "flour" [e.g., 2] that adhered to their outer surfaces. Compositional studies [e.g., 3,4] were limited to cluster analysis techniques that used average glass compositions to infer the major element chemistry of the rock types contributing to the lunar soil. This relationship allowed identities of lunar rock types to be established, whether or not they were collected by the astronauts, and helped to reconstruct, via models, the petrologic evolution of the Moon [e.g., 4].

Recent Detailed Investigations: Fifty years after those first studies, much more is known about lunar impact glasses and the compositional and temporal information they can provide. Importantly, it is widely accepted that lunar impact glasses form most often during impact into regolith [e.g., 5-8] and not rock. Individual glass compositions, rather than cluster averages, give evidence for derivation from local regolith and also from ancient, subsurface, and/or distant regoliths not collected by the astronauts [e.g., 7-9]. Additionally, $^{40}\text{Ar}/^{39}\text{Ar}$ [e.g., 10-13] and U-Pb [e.g., 14,15] formation ages can be measured. When appropriate glass samples are used [11,12], these ages reliably constrain the timing of the lunar impact flux [e.g., 11,13,16]

Current Work: Abundant in the lunar regolith samples, lunar glasses continue to reveal information about the compositional evolution of the Moon. $^{40}\text{Ar}/^{39}\text{Ar}$ ages in particular, provide information on probable recent enhancements of the lunar impact flux [e.g., 11,17], while paleomagnetic studies [e.g., 18] of lunar glasses may be another source of evidence for impact-induced magnetic signatures in lunar samples [e.g. 19]. Impact

glass samples from depth may also provide useful information about the rate of impact gardening, the extent of sampling bias in the Apollo scoops [e.g., 20], and the nature of the solar wind over time.

Conclusions: Lunar impact glasses are supplying a data set with which we can investigate the Moon's geological characteristics and evolution over time, including that of areas not directly sampled by past, current, or future planned missions. These studies also allow us to establish a basis for investigations of impact (and other) glasses that will likely be found in returned Mars and asteroid regolith samples.

References: [1] McKay et al. (1970) *GCA*, **1**, 673-694. [2] Chao et al. (1970) *JGR*, **75**, 7445-7479. [3] Reid et al. (1972a) *Meteoritics*, **7**, 395-415. [4] Reid et al. (1972b) *Proc. 3rd Lun. Sci. Conf.*, 363-378. [5] Delano J.W. et al. (1981) *Proc. Lun. Plan. Sci.*, **12B**, 339-370. [6] Delano J.W. (1986) *JGR*, **91**, D201-D213. [7] Wentworth and McKay (1991) *Proc. Lun. Planet. Sci.* **2**, 185-192. [8] Zellner et al. (2002) *JGR*, **107**, 5102-5115. [9] Delano J. W. (1991) *GCA*, **55**, 3019-3029. [10] Levine J. et al. (2005) *GRL*, **32**, L15201. [11] Zellner N. E. B. and Delano J. W. (2015) *GCA*, **161**, 203-218. [12] Nguyen P. Q. and Zellner N. E. B. (2019) *Geosciences*, **9**(85). [13] Zellner N. E. B. (2017) *OLEB*, **47**, 261-280. [14] Norman M. D. et al. (2013) *76th Met. Soc. Meeting*, Abstract 5163. [15] Zellner et al. (2013) *44th LPSC*, 2539.pdf. [16] Zellner 2019; [17] Zellner et al. (2009) *GCA*, **73**, 4590-4597. [18] Hess K. et al. (2019) *50th LPSC*, 3190.pdf. [19] Crawford and Schultz (1999) *Int. Journ. Impact. Eng.*, **23**, 169-180. [20] Huang et al. (2018) *GRL.*, **45**, 6805-6813. [21] Delano J. W. et al. (2007) *MAPS* **42**, 993-1004.

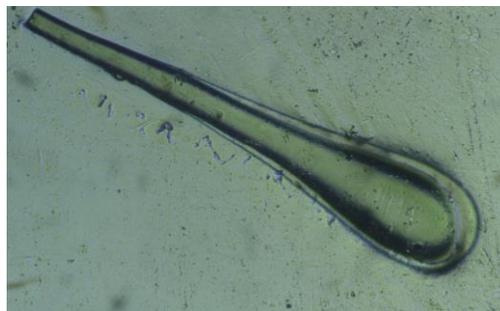


Figure 1. Apollo 16 lunar impact glass (#192) that shows an aerodynamic shape formed when melted regolith was quenched during ballistic flight. Glass is 300 μm from end to end. Compositional details can be found in [21].