NO CHANGE IN THE LUNAR IMPACT FLUX FROM MODELING IMPACT GLASS SPHERULE AGES.

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Motivation: Lunar impact glass spherules are unique because they are interpreted as a direct product of an impact cratering event. The ^{40}Ar/^{39}Ar-derived ages of impact glasses, and spherules in particular, are assumed to be the timing of the most recent impact cratering event that has reset the argon gas of the spherule. Analyses of impact glass spherules in Apollo 14 regolith sample 14163 by Culler et al. [1] show an excess of impact glass spherules with derived ^{40}Ar/^{39}Ar ages of <400 Ma, compared to what would be expected from standard impact flux models for the Moon [2]. Subsequently, impact glass spherules with these young ages have also been reported in Apollo 12 and 16 regolith samples, 12023 and 66031 [3,4].

Although a change in the impact flux in the inner Solar System has been debated [2,5,6], an explanation for the excess of young impact glass spherule ages is an increase in the impact flux during the last 500 Ma. However, biases due to either glass destruction or thermal argon diffusion could have resulted in these young ages. For example, Zellner and Delano [7] accounted for the possibility of argon diffusion occurring in an impact glass spherule, and in doing so, they found a uniform age distribution over the last 1 Ga. Still, the measured ^{40}Ar/^{39}Ar ages of impact glass spherules in regolith samples [1,3,4] show a prominent spike; yet, the geochemical composition data in those samples were not available to account for the correction.

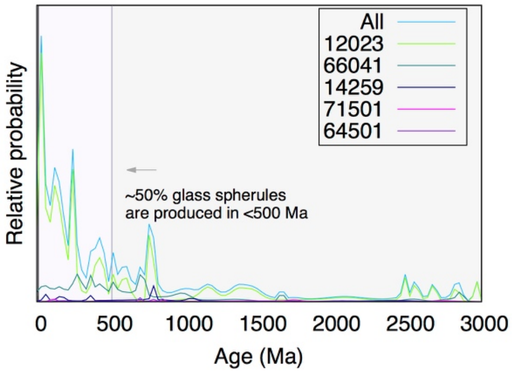

Figure 1: The relative probability plot of lunar impact glass spherules from Apollo 12, 14, 16, and 17 soils [3,7]. The relative impact flux is calculated from a fraction of numbers of impact glass spherule and shards normalized by all five soil samples. The data is taken directly from [3] and [7]. The data of Culler and Hui are not included in this figure.

Although it has been hypothesized that there is a young age bias, this has not been analyzed in detail due to difficulties in modeling the dynamics of lunar regolith samples. By examining the formation, transport, destruction, and sampling of impact glass spherules, we found that both production and sampling had significant influence on the age distribution of the obtained spherules. Whether the impact flux has been changed or not, we suggest that the age record of lunar impact glass spherules may be subject to a bias due to a limited sampling depth that was achievable in the Apollo program. This young age bias can also be promoted by the choice of production model of lunar impact glass spherules. Our results suggest that a future lunar sampling strategy can avoid this depth-dependent bias by accommodating a deeper depth of lunar regolith.

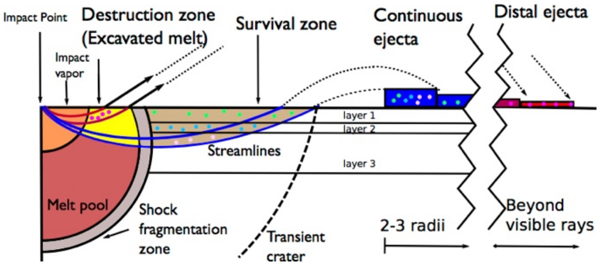

Figure 2: The schematic of model glass spherule zone. The melt zone consists of melt pool (red) and excavated melt zone (yellow). The rest of excavation zone enveloped by streamlines is where any pre-existing spherules from underlying layers can survive. After excavation initiated, excavated materials including model spherules deposit as continuous ejecta and distal ejecta.

Methods: Under a constant impact flux scenario over 3 Gy, we defined a domain of 1 km by 1 km as our simulated Apollo landing site with a model resolution of 10 m/px. Production, transport, destruction, and sampling process of model glass spherules were implemented into CTEM [8-10] (see Figure 2). The production model of glass spherules remains the most uncertain element of our approach. Spherules are thought to originate in an impact melt zone that breaks down into small droplets and then rapidly quenches during ballistic flight [11,12]. From microtektites, terrestrial analogy of impact glass spherules, their occurrences appear to correlate with the deposition distance; most of them are far away from their source crataer. Thus, we considered a cutoff distance for producing glass spherules in CTEM to examine the sensitivity of our simulation's results. A cutoff distance was imposed beyond which glass spherules are deposited. Four cutoff distances (0, 5, 10, and 20 radii) were used, but the cutoff value of 20 radii is derived from the data of size and spatial distribution of terrestrial microtektites sampled from Chicxculub, Chesapeake Bay, and Lake Bosumtwi Crater [e.g. 13].

Our 3D regolith transport code implemented into CTEM is constructed as a layer system that tracks each ejecta layer of an impact cratering event during the 3 Gy-long simulation. At the end of our simulations, our simulated domain included a model stratigraphy of hundreds of layers with information on layer thickness, age, and the concentration of glass spherules.

We also incorporate the effect of craters beyond the simulated domain (in a super domain). This effect becomes significant because the deposition of ejecta in rays from large craters can be a major contributor to samples at a given location on the Moon [e.g., 10]. To account for the stochastic variability of large craters, we ran fifty simulations and considered 500,000 model landing sites in total. Since each of our model sites records a unique history of ejecta layers, we can numerically sample the upper surface in a way that is somewhat akin to how lunar astronauts collected a soil sample. We examined two model depths, 10 cm and 3 m. The depth of 10 cm is comparable to the typical lunar Apollo sampling depth; the depth of 3 m is the length of the deepest lunar drilling core. For any model glass spherules tagged with a specific age, we modeled the likelihood of impact probability by using Gaussian distribution with an assumed error of 50 Ma, in which the amplitude of relative probability is governed by the number of model glass spherules within a model sample. As a result, our model impact probability can be directly compared with observation data set of five soil samples in Figure 1.

Results: We examined how varying both sampling depth and production cutoff distance affected our model sample age probability plots. Figure 3 shows our results with varying cutoff distances for the same sampling depth of 10 cm. The relative probability plot resembles observation data in Figure 1 when model glass spherules are only generated beyond >10 radii from a crater. The spike in the last 500 Ma becomes defined when model glass spherules are only generated beyond 20 radii. On the other hand, if melt within the continuous ejecta blanket is assumed to result in glass spherules, the age distribution is more uniform.

Assuming model glass spherules are produced only beyond 20 radii from a crater, we examined how age distributions of glass spherule populations change with varying depth. As we sampled deeper (1 m and 3 m), the magnitudes of relative probabilities of model glass spherule populations older than 1 Gy become more visible as shown in Figure 4a and 4b. The relative probability of model regolith samples collected down to 3 m is less biased than samples collected from a shallow depth.

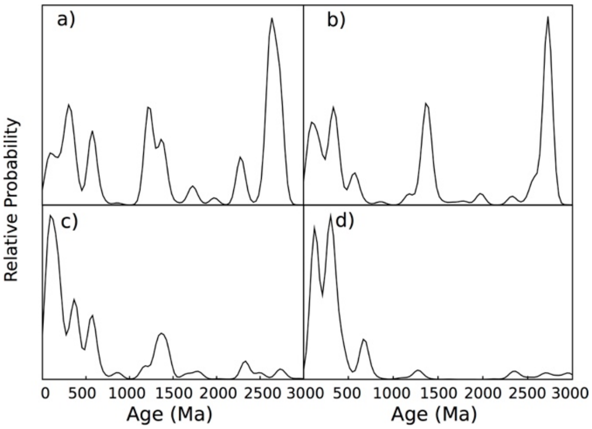

Figure 3: The relative probability plot calculated from our fifty simulated surfaces with four different cutoff distances: a) 0, b) 5, c) 10, and d) 20 radii from a crater.

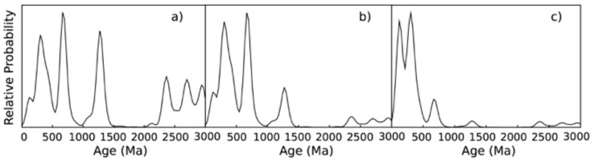

Figure 4: The relative probability plot calculated from our fifty simulated surfaces with three sampling depths: a) 3 m, b) 1 m, and c) 10 cm.

Conclusions: A preponderance of young model sample ages similar to the observed sample age distributions is seen when either the simulated depth is as shallow as 10 cm, consistent with a typical sampling depth from which Apollo soils were taken, or when the occurrence of model glass spherules in the ejecta is beyond 10 radii from a crater, consistent with terrestrial microtektite constraints.

These results (e.g., Fig. 4) are consistent with the excess of young lunar impact glass spherules being the result of the sampling depths where lunar soils were collected, rather than a significant change in the impact flux in the last 500 Ma.

References: [1] Culler, T. et al. *Science* 287, 1785-1788, 2000. [2] Neukum, G. et al. in *Chronology and evolution of Mars*, pp. 55-86, 2001. [3] Levine, J. et al. *Geo. Res. Lett.* 32, L15201, 2005. [4] Hui S. et al., *Proc. 9th Australian Space Sci. Conf.* National Space Society of Australi Ltd., Sydney, pp.43-54, 2010. [5] Shoemaker, E. et al. *GSA Special Paper* 247, 155-170, 1990. [6] Quantin, C. et al. *Icarus* 186, 1-10, 2007. [7] Zellner, N. and Delano, J. *Geoch. et Cosmo. Acta* 161, 203-218, 2015. [8] Richardson, J. *Icarus*, 204, 697-715, 2009. [9] Minton, D. et al. *Icarus* 247, 172-190, 2015 [10] Huang, Y.-H. et al. *JGR: Planets* 122, 1158-1180, 2017. [11] Delano, J. et al. *Proc. LPSC*, vol. 12, 339-370, 1982. [12] Melosh, H. and Vickery, A. *Nature* 350, 494, 1991. [13] Glass, B. and Simonson, B. *Distal impact ejecta layers: A record of large impacts in sedimentary deposits*, 2013.