INVESTIGATING A POTENTIAL IMPACT PULSE IN THE EARTH-MOON SYSTEM ~2 GA. Amy L. Fagan[1], Katherine H. Joy[1,2,3], Donald D. Bogard[1,2], and David A. Kring[1,2], [1]Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058, USA; [2]NASA Solar System Exploration Research Virtual Institute; [3]School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, UK.

Introduction: The lunar regolith contains a record of the types of material impacting the Earth-Moon system through time. It was recently shown that Apollo 16 ancient regolith breccias contain relic fragments of the impactors hitting the Moon >3.4 Ga, which were characterized as primitive chondritic material [1]. These relics provide a direct measure of the types of material delivered to the Earth-Moon system following the formation of Imbrium basin. A younger set of breccias and soils found at Apollo 16 contain relics with greater compositional diversity than their more ancient counterparts, suggesting a variety of projectiles hit the lunar surface in the post-basin-forming epoch [1]. Further examination of relic materials preserved in lunar regolith breccias will help to elucidate the temporally changing bombardment of the inner solar system and, in particular, the post-cataclysm impact flux (Fig. 1).

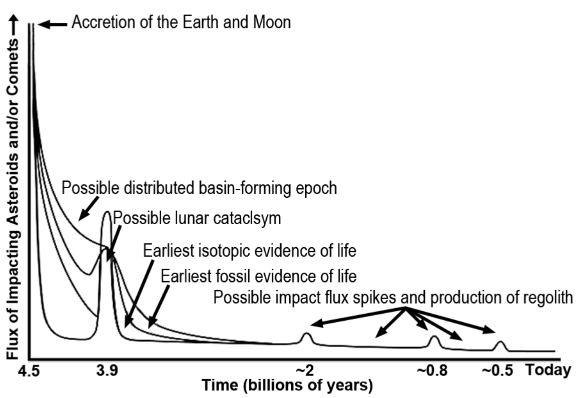

Fig. 1. Schematic diagram of Earth-Moon bombardment models with potential pulses of increased impact activity at ~ 2, 0.8, and 0.5 Ga (after [2]).

Several pulses of increased impact activity may have occurred in the post basin-forming epoch (Fig. 1). An increase in impact activity at ~0.5 Ga (Fig. 1) was apparently prompted by the disruption of the L-chondrite parent body at ~0.47 Ga (e.g., [3]), which produced a large number of shocked L-chondrites with that age [3] and several terrestrial impact craters shortly thereafter (e.g., [4, 5]). Another pulse may have occurred at ~0.8 Ga (Fig. 1), based on the impact ages observed in several ordinary chondrites [6-8] and the inferred age of Copernicus crater (e.g., [9]).

There are hints of an additional impact pulse (Fig. 1) at ~2 Ga [10] based on the ages of the Vredefort (~2 Ga [11]) and Sudbury (~1.85 Ga [12]) terrestrial impact structures and LL chondrite meteorite impact ages (e.g., [13]). More recently, this potential impact pulse has been reinforced by a 1.9 Ga impact-reset age from zircon and phosphate in Apollo 15 melt breccia 15405 [14] and by ~1.8 Ga model ages of 2 lunar crater floors as determined by superposed crater size-frequency distributions [15]. Although at least two large terrestrial impact structures formed ~2 Ga, the collisional history of the Proterozoic Earth is poorly constrained among terrestrial samples (e.g., [2]). Therefore, we turn our attention to the lunar regolith breccias, which serve as time capsules for the bombardment history of the Earth-Moon system. In particular, we focus on samples with closure ages similar to the implied impact pulse at ~2 Ga.

Sample Closure Ages: The trapped $^{40}Ar/^{36}Ar$ ratio (Ar_{Tr}) in a regolith breccia can be used to determine the time of sample closure to further solar wind (and projectile) input through burial (e.g., [16-19]). The relationship between Ar_{Tr} and time was recently recalibrated [20, after 19], producing the formula: $t=1.2103\ln(Ar_{Tr})+0.7148$, where t is the model closure age (Ga). Using this new calibration, we have calculated the closure ages of 56 lunar regolith breccias from the Apollo, Luna, and meteorite collections [21] (Fig. 2).

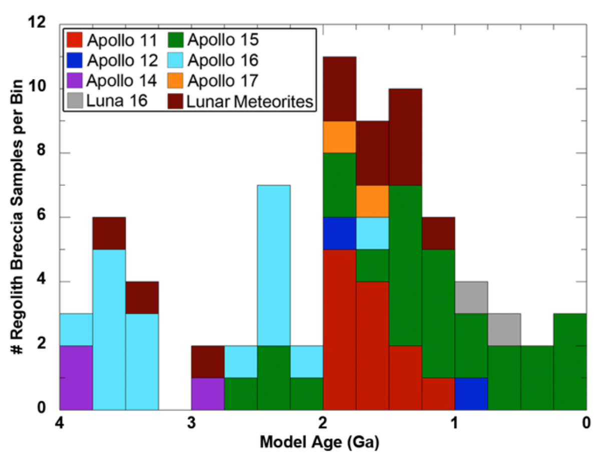

Fig. 2. Stacked histogram of regolith breccia closure ages calculated in this study; Apollo 16 ages were calculated by [20]. Bin size is 0.25 Ga.

Collectively, the data indicate that regolith breccias can provide a fairly complete record of surface processes over the past 4 Ga. From that collection of samples [21], we selected 9 with closure ages ranging from ~2.4 to ~1.5 Ga.

Analytical Methods: Thin sections of selected samples were examined using an optical microscope and the NASA JSC JEOL-5910LV Field Emission-Scanning Electron Microscope (FE-SEM), which collected qualitative element and back-scatter electron maps to identify potentially exotic lithic and mineral fragments (see [22] for details of FE-SEM element mapping technique). Fragments of interest were then analyzed using the NASA JSC Cameca SX100 electron microprobe to determine mineral compositions.

Identified Relics: Three samples (10021,35; 10060,33; and 15287,7) with closure ages 1.79 to 1.76 Ga were each found to contain at least one particle with non-lunar chemistry; analyses of the remaining 6 samples are ongoing.

10021,35 (t~1.79 Ga). One ~30 µm long isolated enstatite grain ($En_{82\text{-}83}Fs_{16\text{-}17}Wo_1$) has a non-lunar Fe/Mn ratio of 20 to 23 (Fig. 3) and Mg# of 83 to 85. This is similar to the composition of pyroxene in several H chondrites (e.g., Seoni, Conquista, and Uberaba [23-25]), suggesting an origin from a similar source.

10060,33 (t~1.76 Ga). A ~130×135 µm lithic clast consists of forsteritic olivine (typically $Fo_{85\text{-}89}$) and plagioclase (An_{79}). Olivine has a non-lunar Fe/Mn ratio (~45 to 65; Fig. 3) and compositional similarities to several CO chondrites (i.e., ALHA77307, Isna, and Lance, [26]). Additionally, the plagioclase is compositionally similar to that of plagioclase-bearing chondrules in Kainsaz, a CO chondrite [27]. Based on compositional affinities to some CO chondrites, the lithic clast may be from a similar source.

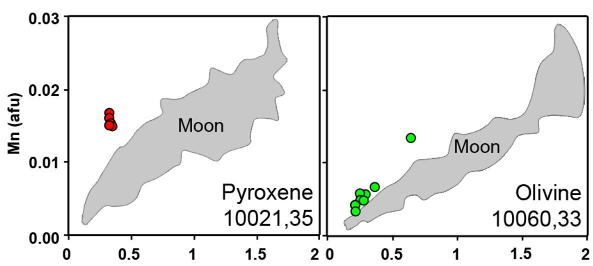

Fig. 3. Mn and Fe data from 10021 and 10060 relics compared to lunar (grey field) compositions. Modified from [1].

15287,7 (t~1.76 Ga). A moderately elongate spherule (~155×190 µm) is composed of metallic grains with ~75 to 78 wt% Fe and 22 to 23 wt% Ni; minor amounts of Co (~1 wt%) and P (0.1 to 0.5 wt%) are also present. The mesostasis has higher concentrations of P (7.7-8.3 wt%), S (1.1 to 1.4 wt%), and Ni (26.4 to 27.2 wt%). The Co/Ni ratio of the metallic grains is 0.05, which is chondritic (e.g., [28]). Although a link to a specific type of meteoritic material has not yet been made, the significant Ni content suggests that the spherule has a non-lunar provenance.

Relic Diversity. The relics identified here provide information about the post basin-forming projectile record, which is more diverse than during the final stages of the basin-forming epoch [1]. Relics found in 10021 and 10060 suggest that the Earth-Moon system was impacted by bodies with compositional similarities to H and CO chondrites, respectively, prior to sample closure ~1.79 to 1.76 Ga. Similarly, 3 relics found in 60255 [1], which closed ~1.7 Ga [20], indicate the presence of carbonaceous chondrite projectiles, with at least one relic suggesting a CI chondrite source [1]. Together, these samples indicate that the Earth-Moon system experienced bombardment from multiple projectile types circa 2 Ga. Thus far, we have not encountered any evidence of a dominant impactor population that might be consistent with the breakup of a planetesimal and the resultant pulse of cratering like that seen at ~0.5 Ga. Identifying and classifying additional relics from lunar regolith breccias with similar closure ages will help to constrain and better characterize the impactor population during the ~2 Ga interval of time.

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