Investigating a potential impact pulse in the Earth-Moon system ~2 Ga

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INVESTIGATING A POTENTIAL IMPACT PULSE IN THE EARTH-MOON SYSTEM ~2 GA. Amy L. Fagan1, Katherine H. Joy1,2,3, Donald D. Bogard1,2, and David A. Kring1,2, 1Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058, USA; 2NASA Solar System Exploration Research Virtual Institute; 3School 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 ($\text{Ar}_{\text{T}}$) 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 $\text{Ar}_{\text{T}}$ and time was recently recalibrated [20, after 19], producing the formula: $t=1.2103\ln(\text{Ar}_{\text{T}})+0.7148$, 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).

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 (~1.79 Ga). One ~30 µm long isolated enstatite grain (En82-83Fs16-17Wo1) 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 (~1.76 Ga). A ~130×135 µm lithic clast consists of forsteritic olivine (typically Fo85-88) and plagioclase (An96). 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 Kainsz, a CO chondrite [27]. Based on compositional affinities to some CO chondrites, the lithic clast may be from a similar source.

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.