UNRAVELING THE BOMBARDMENT HISTORY OF THE EARTH-MOON SYSTEM ~2 BILLION YEARS AGO. Amy L. Fagan[1,2,3], Katherine H. Joy[1,2,4], 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]Geosciences and Natural Resources Department, 331 Stillwell Building, Western Carolina University, Cullowhee, NC, 28723, USA (alfagan@wcu.edu); [4]School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester, M13 9PL, UK.

Introduction: The lunar regolith has served as a witness to the bombardment history of the Earth-Moon system throughout time and preserves the vestiges of the temporally changing projectile population. Relic fragments of impactors that hit the Moon >3.4 Ga were recently identified within ancient Apollo 16 regolith breccias and were characterized as primitive chondritic material [1]. However, breccias with closure ages that post-date the basin-forming epoch contained relics with greater compositional diversity than their ancient counterparts, suggesting a more diverse projectile population in the post-basin-forming epoch [1]. That initial study suggests that a broader survey of relic materials preserved in lunar regolith breccias could reveal additional details about the flux of material to the Earth-Moon system and how it changed in the post-cataclysm epoch (Fig. 1).

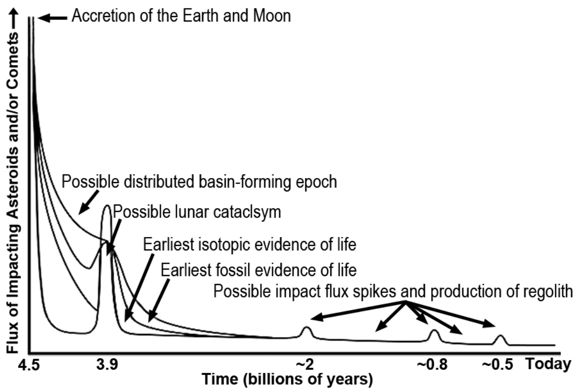

Fig. 1. Schematic diagram of Earth-Moon bombardment models with potential pulses of increased impact activity at ~ 2 Ga, 0.8 Ga, and 0.5 Ga (modified from [2]).

Two pulses of increased impact activity have been suggested for ~0.5 Ga and ~0.8 Ga during the post-basin-forming epoch (Fig. 1). The apparent disruption of the L chondrite parent body occurred at 0.47 Ga (e.g., [3]) as indicated by shocked L-chondrites and the production of several terrestrial impact craters shortly thereafter (e.g., [4, 5]). Several lines of evidence suggest another pulse at ~0.8 Ga such as impact ages of some ordinary chondrites [6-8], the inferred age of Copernicus crater (e.g., [9]), and most recently, the ages of nine impact glasses from Apollo 14, 16, and 17 [10].

There is growing evidence of an additional pulse at ~2 Ga [11]. This is approximately the age of both the Vredefort (2.02 Ga [12]) and Sudbury (1.85 Ga [13]) terrestrial impact structures as well as the inferred age of the lunar crater, Autolycus (~2.1 Ga, [14]) and the model ages of 2 lunar crater floors (Vavilov and Hayn) determined by crater size-frequency distributions (~1.8 Ga, [15]). Further support of a pulse of activity ~2 Ga is given by similarly aged LL chondrite meteorite impact ages (e.g., [16]), an impact-reset age from zircon and phosphate in Apollo 15 melt breccia 15405 (~1.9 Ga, [17]), and the ages of several regolith glasses from Apollo 11 regolith sample 10084 (~2 Ga, [18]).

In this study, we examine lunar regolith breccias with closure ages ~2 Ga [19] to determine the types of projectiles that were hitting the Moon and Earth at that time. Examination of relics preserved within these breccias may help to determine if the projectile population was dominated by a single type of material and, thus, reflective of a planetesimal break-up event.

Analytical Methods: We selected 9 regolith breccias from Apollo 11, 15, and 17 with closure ages [19] ranging 1.47 to 2.35 Ga to sufficiently bracket the potential impact pulse at ~2 Ga. We identified potential relic material from thin sections of these selected samples using an optical microscope as well as qualitative element and back-scatter electron maps (see [20] for details of element mapping technique) generated by the NASA JSC JEOL-5910LV Field Emission-Scanning Electron Microscope (FE-SEM). Lithic fragments of interest were then analyzed using the NASA JSC Cameca SX100 electron microprobe to derive mineral compositions. Fragments with non-lunar FeO/MnO ratios and Mg# are identified as material from surviving projectiles.

Identified Relics: Eleven relics were identified from 4 samples with closure ages [19] ranging 1.76 to 1.92 Ga (10021,35; 10060,33; 15287,7; 15465,94). No relics were found in 5 additional samples with closure ages [19] ranging 1.47 to 2.35 Ga (15459,474; 15467,4; 15528,4; 15565,57; 79135,14). We identified four types of relics: (1) olivine and plagioclase-bearing clasts, (2) olivine and glass-bearing clasts, (3) a metallic spherule, and (4) an isolated enstatite grain.

Olivine and Plagioclase-bearing Clasts: Six of the 11 relics are lithic clasts from 10021,35; 10060,33; and 15465,94 that consist of forsteritic olivine (Fo_{67-89}) and anorthitic plagioclase (An_{59-91}). The olivine within these relics have non-lunar FeO/MnO ratios of ~40 to 69 (Fig. 2, blue symbols). Some olivine and plagioclase display compositional similarities (Fe, Mn, Cr, Al) to CO chondrites (e.g., ALHA77307, Isna, Lance, Kainsaz [21, 22]). Many olivine grains also have similar Fo and FeO/MnO ratio to a relic clast (Fig. 2) identified in 60255,110 (t~1.7 Ga [23]), which has oxygen isotopes similar to bulk rock CI chondrites [1].

Olivine and Glass-bearing Clasts: Three relics from 10021,35 and 15287,7 consist of forsteritic olivine (Fo_{56-85}) set in a glass matrix and are texturally distinct from primary lunar crystalline spherules (e.g., [24]). Many of the olivine grains within these relics have distinctly non-lunar FeO/MnO ratios (~53 to 72; Fig. 2, red symbols). However, some olivine is zoned with FeO/MnO ratios that stray into the lunar field (~74 to 93, Fig. 2, red symbols).

Metallic Spherule: A spherule (~155×190 µm) in 15287,7 (t~1.76 Ga) contains metal grains with ~75 to 78 wt% Fe, 22 to 23 wt% Ni, and minor amounts of both Co (~1 wt%) and P (0.1 to 0.5 wt%). The Co/Ni ratio of these grains is chondritic (~0.05; e.g., [25]), and the high Ni content implies that the spherule has a non-lunar provenance.

Isolated Enstatite Grain: A single, ~30 µm long, isolated enstatite grain ($En_{82-83}Fs_{16-17}Wo_1$) within 10021,35 (t~1.79 Ga) has a non-lunar composition (FeO/MnO: 19 to 23; Mg#: 83 to 85). This grain is compositionally similar to pyroxene from some H chondrites (Seoni, Conquista, Uberaba [26-28]), suggesting an origin from a similar source.

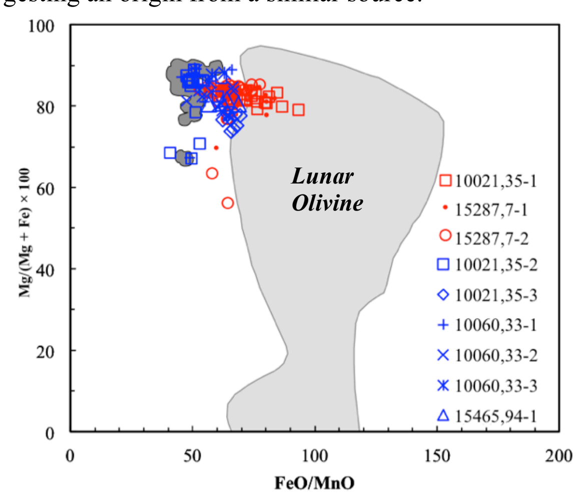

Fig. 2. Olivine compositions from relics in this study (red and blue symbols) in comparison with lunar olivine (light grey field) and olivine from an olivine-phyric relic in regolith breccia 60255,110 (dark grey field, [1]). Red symbols represent olivine from olivine and plagioclase-bearing clasts and blue symbols represent olivine from olivine and glass-bearing clasts. Modified from [1].

The Projectile Population ~2 Ga. The relics identified here reflect the projectile population hitting the Moon, and by inference the Earth, at ~2 Ga. The diversity of the relics found in this study and by [1] suggests that the Earth-Moon system was impacted by projectiles from multiple sources prior to sample closure ~1.76 to 1.92 Ga, as at least 4 types of relics have been identified. Compositional similarities exist between some relics and at least two different types of carbonaceous chondrites (CO and CI), whereas others are similar to material from H chondrites or an Fe-Ni-bearing projectile. Most of the relics identified here and in [1] point to a source compositionally similar to carbonaceous chondrites, which might hint at a preponderance of such a projectile population circa 2 Ga. However, the impactor population does not appear to be dominated by a single type of material (i.e., one type of carbonaceous chondrite). Thus, evidence of a planetary breakup event ~2 Ga, such as that at ~0.5 Ga, has not yet been found.

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