MULTIPLE IMPACTORS EVIDENCED IN APOLLO 16 LUNAR IMPACT-MELT BRECCIAS. J. G. Liu[1,2] and R. J. Walker[1]. [1]Department of Geology, University of Maryland, College Park, USA. [2]Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Canada (gobyliu@gmail.com).

Introduction: The Earth's mantle is characterized by relatively high (~200 times lower than those of CI chondrites) and nearly chondritic relative abundances of highly siderophile elements (HSE) [1]. These characteristics are inconsistent with core-mantle equilibrium [2], and most likely implicate late accretion of ~0.5% additional planetary mass after cessation of core segregation. A record of the number and types of late accreted materials to Earth, however, has been obscured by active plate tectonics.

The Moon, by contrast, provides a record of the end stages of late accretion in the form of large basins. The basin-forming impacts have been suggested to be part of a putative late heavy bombardment of the inner solar system [3]. Because exogenous materials from impactors are typically greatly enriched in HSE compared to the lunar crust [4-6], the relative abundances of HSE in lunar impact-melt breccias, which are associated with basin formation, can be used to fingerprint the nature of impactors responsible for these events [7-9]. Comparisons of the relative abundances of the HSE in impact melt rocks to various meteoritic materials are commonly made. The relative abundances of the HSE in the impactors can be obtained by using $^{187}Os/^{188}Os$ as a proxy for long-term Re/Os, and by determining the slopes of linear trends generated via regressions of Ir against abundances of other HSE from several sub-samples of an impact-melt breccia.

Here we present new HSE results for Apollo 16 impact-melt breccias and use these data, in combination with published data for other lunar impact-melt breccias, to investigate the chemical and isotopic nature of impactors involved in the basin forming events and contributed materials to the breccias present at the Apollo 16 landing site.

Samples: Lunar impact melt breccias from the Apollo 16 landing site investigated here include diverse lithologies represented by samples 67095, 68416, 65095, and 60016. Sample 67095 is a basaltic impact melt rock collected from the rim of the North Ray Crater. Although the ^{40}Ar-^{39}Ar system is disturbed, it suggests a formation age of 3850-3900 Ma [10]. This sample contains substantial metal in the form of globules, which are highly enriched in the HSE. Sample 68416 is a crystallized basaltic breccia chipped from the top of a boulder from South Ray Crater. This sample has relatively low metal abundances. A Rb-Sr internal isochron age of 3840±10 Ma has been reported [11]. Sample 65095 is a fragmental feldspathic regolith breccia collected from the lower slope of Stone Mountain. For HSE work, an impact-melt clast derived from the regolith breccia was examined. This subsample formed at 3850-3900 Ma, based on ^{40}Ar-^{39}Ar [12]. Sample 60016 is a polymict regolith breccia collected near the Lunar Module. Two impact-melt clasts derived from this regolith breccia were examined: 60016.286b and 60016.290b. ^{40}Ar-^{39}Ar ages for the same clasts are 3869±5 Ma and 3958±6 Ma, respectively [13].

Analytical Methods: Analytical procedures followed those reported in Puchtel et al. [8]. Each breccia specimen (<2g) was gently broken up using an alumina mortar and pestle, and split into approximately ten sub-samples (~10-100 mg). The subsamples were lightly ground. Each sub-sample was then sealed with the appropriate amounts of HSE spikes, 2ml of conc. HCl, and 3ml of conc. HNO_3 in 10 ml pre-cleaned Pyrex Carius tubes and digested at 270^{o}C for >72 hours. Osmium was separated from the rest of the HSE by solvent (CCl_4) extraction and analyzed using N-TIMS. The rest of the HSE were separated and purified by anion exchange chromatography and analyzed using ICP-MS.

Results: The average $^{187}Os/^{188}Os$ of 10 sub-samples of 67095 is 0.1349±7 ($2\sigma_{mean}$). Five metal globules separated from 67095 are characterized by more variable and more radiogenic $^{187}Os/^{188}Os$ ratios, averaging 0.1369±12. Sample 65095 is characterized by an average $^{187}Os/^{188}Os$ of 0.1392±14 (n=8), and the two clasts from regolith breccia 60016 (286b and 290b) have essentially identical average $^{187}Os/^{188}Os$ of 0.1383±7 (n=7) and 0.1390±8 (n=9), respectively. These ratios are comparable to those reported by [9] for samples 60315 and 67935. Collectively, the average isotopic ratios of these samples are similar to those of Apollo 15 impact-melt breccias, but significantly more radiogenic (higher long-term Re/Os) than average ratios reported for Apollo 17 (Serenitatis) impact melt rocks (**Fig. 1**).

Sample 68416 is characterized as having a substantially much less radiogenic average $^{187}Os/^{188}Os$ of 0.1297±5 (n=10). This ratio is more radiogenic than average ratios of 0.1277±4 (n=11) and 0.1271±9 (n=10) that were previously reported for samples 67955 and 67915 by [9].

As with Os isotopic compositions, the sub-samples of Apollo 16 breccias show considerable variations in the absolute and relative abundances of the HSE, e.g., Ir ranging from 1.1 to 7.2 ng/g for 67095, and 17.2 to

29.8 ng/g for 60016.290b. Iridium is generally well correlated with other HSE in sub-samples. Similar to many other Apollo breccias [8-9,14], the y-intercepts of regression lines for most elements in most samples are statistically indistinguishable from zero, consistent with target material (lunar crust) being relatively free of HSE. However, some trends for samples 60016 and 65095 (Ru/Ir, Pt/Ir and Pd/Ir), are characterized by non-zero intercepts that most likely reflect mixtures of at least two meteoritic components.

Combining our new data with those reported by [9], the slopes of Ir-HSE linear correlations of the Apollo 16 impact-melt breccias continue to show very large variations, most notably in Ru/Ir and Pd/Ir ratios that range from chondritic to suprachondritic values (**Fig. 1**).

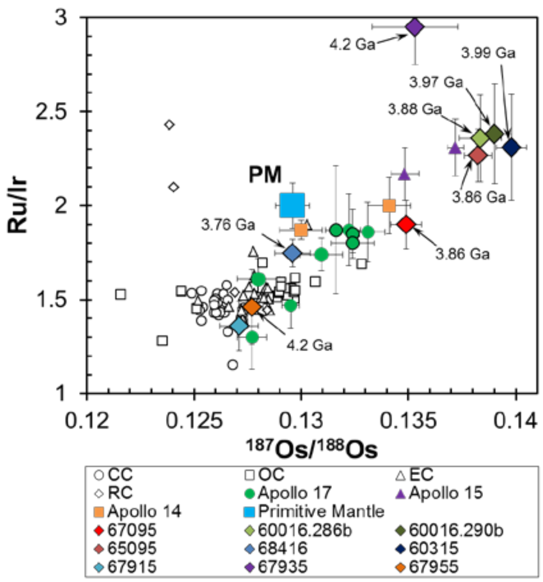

Fig. 1. $^{187}Os/^{188}Os$ *vs.* Ru/Ir for Apollo 16 (solid diamonds marked with formation ages) and other lunar impact melt breccias from this study and literature [8-9] in comparison with chondrites [4-5] and the estimate of the Earth's primitive mantle (PM) [1,15].

Discussion: The range of HSE ratios defined by Apollo 16 impact melt rocks essentially encompasses the ranges defined by Apollo 14, 15 and 17 impact breccias [8-9,14]. Given that the Apollo 16 landing site is located within highlands terrain, relatively distal from the lunar basins, the observed HSE data suggest that the Apollo 16 rocks sample ejecta of multiple, major impacts that created the surrounding lunar basins. The complex ejecta components seen in Apollo 16 breccias are consistent with the temporal range of the materials we analyzed, with ages that span more than 100 Ma.

From the analyzed Apollo lunar impact-melt breccias, their relative HSE compositions, e.g., $^{187}Os/^{188}Os$, Ru/Ir and Pd/Ir, mostly are suprachondritic with a few within the range of the major chondrite groups (Fig. 1). It is most likely that the Earth received similar meteoritic materials as the Moon during their late accretionary histories. The primitive mantle of the Earth is characterized by coupled suprachondritic Ru/Ir and Pd/Ir ratios, as well as high $^{187}Os/^{188}Os$ (the $^{187}Os/^{188}Os$ for PM shown in Fig. 1 is a minimum estimate [16]). Of note, many of the lunar impact melt breccias from multiple sites are characterized by relative enrichments comparable to or greater than observed in the primitive mantle (**Fig. 2**). Thus, impactors involved in the late accretionary history of the Earth, appear to be well represented in the late heavy bombardment of the Moon, presumably long after most of the late accretionary mass was added to Earth's mantle.

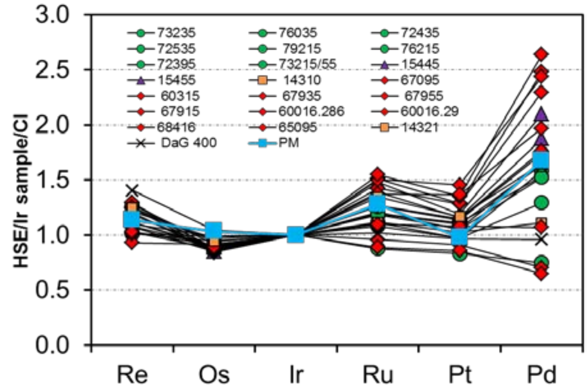

Fig. 2. CI chondrite-normalized HSE/Ir patterns for Apollo impact-melt breccias [8-9, 14, this study] and lunar meteorite (DaG 400), as well as the Earth's primitive (upper) mantle (PM) [1].

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