LATE HEAVY BOMBARDMENT OF THE MOON: EVIDENCE FROM Os ISOTOPE AND HIGHLY SIDEROPHILE ELEMENT CHARACTERISTICS OF LUNAR IMPACT-MELT BRECCIAS.
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Introduction: Impact-generated melts commonly incorporate exogenic materials from impactors that are typically enriched in highly siderophile elements (HSE) (e.g., chondrites and iron meteorites; [1, 2]) compared to endogenic planetary crusts, such as the lunar crust [3]. The relative abundances of the HSE in impact-melt breccias can, therefore, be used to fingerprint the nature of impactors responsible for basin-forming events on the Moon (e.g., [4, 5]). Comparisons to various meteoritic materials are commonly made by determining the relative abundances of HSE using $^{187}Os/^{188}Os$ (a proxy for long-term Re/Os) and slopes of linear trends generated via regressing abundances of Ir against abundances of other HSE. Here, we present new results for Apollo 15, 16, and 17 impact melt breccias and use these data, in combination with previously published data, to investigate the chemical and isotopic nature of impactors that contributed to basin forming events near these landing sites.

Samples: Lunar impact melt breccias from Apollo 15 (15445 and 15455), 16 (67095), and 17 (73235, 72435, 72535, 76035, and 76055) landing sites are the target of this study. The matrix of sample 15445, similar to 15455, is a fine-grained dark breccia. Both 15445 and 15455 were found on the rim of Spur Crater, and are thought to represent ejecta from the Imbrium Basin. Sample 67095 is a basaltic impact melt rock that was collected from the rim of the North Ray Crater. Sample 73235 is an aphanitic melt breccia collected from the regolith at Station 3 at the base of South Massif. Sample 72535 is a fine-grained, clast-bearing poikilitic impact melt breccia covered with micrometeorite craters that was collected from the landslide off of South Massif. Sample 72435 is a poikilitic rock that was chipped from a large melt-rock boulder at Station 2. Both 76035 and 76055 were collected near a boulder at Station 6. Sample 76035 is a poikilitic breccia, while 76055 is a polymict breccia, an assemblage of aphanitic breccia clasts.

Analytical Methods: Analytical procedures followed those reported in Puchtel et al. [5]. Each breccia specimen (1-2 g) was gently broken up using an alumina mortar and pestle and divided into approximately ten ~30-300 mg sub-samples. Any granulitic (for Apollo 17 rocks) or exterior material was removed using a dry-cut saw blade. Each sub-sample was then sealed with the appropriate amounts of Re-Os and HSE spikes, 3ml of conc. HNO_3, and 2ml of conc. HCl in 10 ml pre-cleaned Pyrex Carius tubes and digested at 270°C for >72 hours. Osmium was separated from the rest of the HSE by solvent extraction and analyzed using NTIMS. The rest of the HSE were separated and purified by anion exchange chromatography and analyzed using a MC-ICP-MS. Average blanks (pg) were: Re 1.4, Os 0.1, Ir 0.4, Ru 5.1, Pt 4.2, and Pd 2.3. The blanks constituted generally less than 0.5 % for Os and Ir, 2 % for Ru, Pt and Pd, and up to 10 % for Re of the total element analyzed. The HSE data were regressed using ISOPLOT [7].

Results: The average $^{187}Os/^{188}Os$ of nine sub-samples of 73235 is 0.1309±10 ($2\sigma_{mean}$), slightly higher than that of 11 sub-samples of 73215 and 73255 examined previously (0.1295±4 [5]) and that of polymict breccia 76055 (0.1279±10, n=10). In contrast, this ratio is somewhat lower than averages for various poikilitic samples examined here and previously [5]: 0.1322±5 for 72435 (n=9), 0.1316±5 for 72535 (n=7), 0.1329±3 for 76035 (n=4), and 0.1324±7 for 72395 and 76215 (n=22).

In contrast to Apollo 17 impact melt rocks, 10 sub-samples of Apollo 16 sample 67095 yield a substantially higher $^{187}Os/^{188}Os$ of 0.1349±7, which is comparable to that of a poikilitic Apollo 16 breccia 60315 reported by [6]. Apollo 15 sample 15445 has HSE characteristics similar to Apollo 16 sample 67095 with an average $^{187}Os/^{188}Os$ = 0.1348±6 (n=10). In contrast, sample 15455 is characterized by a significantly higher $^{187}Os/^{188}Os$ of 0.1372±6 (n=11).

The sub-samples of Apollo 17 breccias show a relatively narrow range of Ir contents (e.g., 1.0 to 3.9 ng/g for 73235, 1.5 to 12.3 ng/g for 72435, and 5.6 to 13.9 ng/g for 76035). Sub-samples of Apollo 16 impact melt rock 67095 show a similar Ir range of 1.1 to 7.2 ng/g. Iridium is generally well correlated with other HSE in all sub-samples. Ru-Ir and Pd-Ir regressions show some scatter not visibly associated with sample petrology. The y-intercepts for the Apollo 15, 16 and 17 breccias are generally statistically indistinguishable from zero, consistent with target material being relatively free of HSE, except for sample 76055 that may represent a mixture of at least two meteoritic components, as suggested by positive y-intercepts for Ru, Pt, and particularly Pd. Thus, the slopes of regression lines for Ir *vs.* HSE most likely represent the relative abundances present in the dominant HSE-rich impactors [e.g., 4, 5]. The three Apollo 17 poikilitic samples show similar elevated Ru/Ir and Pd/Ir, relative to the major chondrite groups, as do the other previously measured poikilitic rocks [5, 6] (Fig. 1), while the aphanitic sample 73235 has a slightly lower, but still suprachondritic, Ru/Ir ratio.

The Apollo 16 basaltic melt breccia 67095 has suprachondritic Ru/Ir and Pd/Ir ratios that are comparable to the four Apollo 17 samples, as well as those of the Apollo 16 poikilitic breccia 60315 reported by [6]. The two Apollo 15 breccias have similar or slightly higher Ru/Ir and Pd/Ir ratios than 67095.

Discussion: Our new HSE results, combined with results from [5], show that the Apollo 17 poikilitic breccias from three geographically separate stations appear to have a single dominant impactor signature characterized by suprachondritic $^{187}Os/^{188}Os$ (i.e., Re/Os), Ru/Ir, and Pd/Ir ratios (Fig. 1). Of greatest note is that the data for the new aphanitic sample 73235 differ from the previous results for the Apollo 17 aphanitic breccias 73215 and 73255 [5]. The new aphanite has only slightly lower Ru/Ir and $^{187}Os/^{188}Os$ than the poikilitic Apollo 17 samples (Fig. 1), indicating that some aphanitic impact melt breccias have an HSE signature similar to that of the poikilitic rocks. This, in turn, may suggest that Apollo 17 both poikilitic and aphanitic rocks may have been generated by the same impact, most likely, the one that created the Serenitatis basin.

Compared to the poikilitic Apollo 17 breccias, the higher $^{187}Os/^{188}Os$ ratios of the Apollo 16 basaltic melt breccias 67095 and poikilitic melt breccia 60315 [6], as well as the two Apollo 15 breccias, appear to indicate a different type of impactor with a higher Re/Os, for at least some Apollo 15 and 16 melt breccias. Alternately, the different isotopic compositions may reflect some unidentified fractionation process that affected the relative abundances of the HSE during formation of the melt breccias.

Assuming that the Earth received similar meteoritic material as the Moon during their histories of late accretion, the coupled high Ru/Ir and Pd/Ir ratios, as well as $^{187}Os/^{188}Os$ (the $^{187}Os/^{188}Os$ for PM in Fig. 1 is the minimum estimate, [8]), of the primitive mantle can potentially be accounted for by calling on impactors with HSE characteristics that are not present in the chondritic suite sampled by Earth today.

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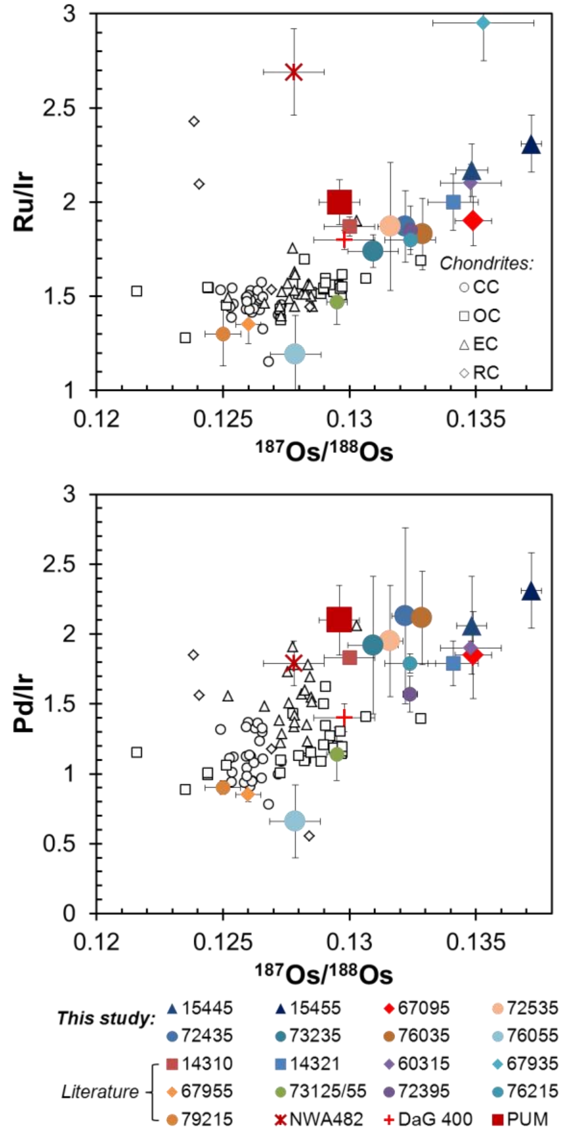

Fig. 1. $^{187}Os/^{188}Os$ vs. Ru/Ir (upper panel) and Pd/Ir (lower panel) for lunar impact melt breccias from this study (large solid symbols: triangle (Apollo 15), diamond (Apollo 16) and circle (Apollo 17)), and the literature (small solid symbols as this study) [5, 6] in comparison with chondrites [1, 2] and the primitive mantle (PM) estimates [9, 10].

References: [1] Horan M.F. et al. (2003) *Chem. Geol.* 196, 5-20. [2] Fischer-Godde M. et al. (2010) *GCA 74*, 356-379. [3] Day J.M.D. et al. (2010) *EPSL 289*, 595-605. [4] Norman M.D. et al. (2002) *EPSL 202*, 217-228. [5] Puchtel I.S. et al. (2008) *GCA 72*, 3022-3042. [6] Fischer-Gödde M. et al. (2010) *LPSC XXXXI*. 2262. [7] Ludwig K.R. (2003) *Berkeley Geochron*. Center Spec. Pub No. 4. [8] Walker R.J. *Chemie der Erde 69*, 101-125. [9] Meisel T. et al. (2001) *GCA 65*, 1311-1323. [10] Becker H. et al. (2006) *GCA 70*, 4528-4550.