CLUES TO LATER IMPACT PROCESSES ON THE MOON FROM A COMPARISON OF IMPACT MELT COATS, REGOLITH BRECCIAS, AND IMPACT MELT BRECCIAS. James M.D. Day[1], Yang Liu[2] [1]Scripps Institution of Oceanography, La Jolla, CA 92093-0244, USA: jmdday@ucsd.edu; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

Introduction: Lunar impact-melt breccias (IMB), regolith breccias and other melt-rocks provide valuable clues to the compositions of impactors striking the Moon after formation of the lunar crust (e.g., [1, 2]). As part of an ongoing study [3], we present new results on impact melt coats (IMC) found on the exteriors of some lunar crustal rocks, and for an IMB, and anorthositic regolith breccias. Our goal is to examine if the record of impactor materials striking the Moon is similar between IMB, IMC and regolith breccias, to better understand localized impact processes on the lunar surface, and to quantify processes of impact contamination and metamorphism that can otherwise hamper interpretation of chronology and identification of primary magmatic processes involved in crust generation [4-6].

Methods: Samples obtained from the NASA curatorial facilities were documented and carefully prepared to make powder sub-aliquots from the fragments of anorthositic regolith breccias, and to separate impact melt coat from ferroan anorthosites materials in (FAN) 65325, 65035 and 60015. Samples were prepared and analyzed using our standard analytical procedures to obtain major- and trace-element abundances, as well as ^{187}Re-^{187}Os and highly siderophile element abundance systematics (e.g., [7, 8]). We compare these measurements with data that we recently reported for 66095 [9], and with published IMB data.

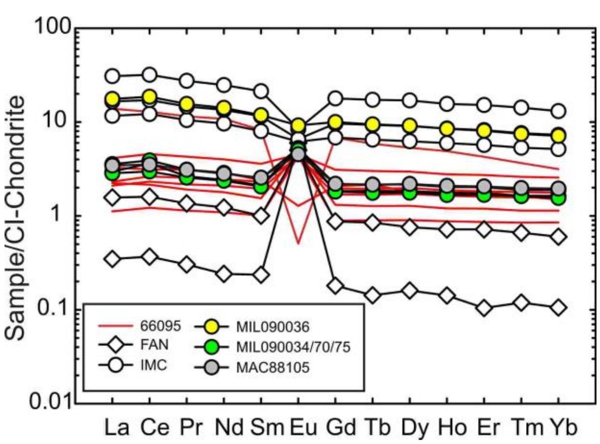

Figure 1: CI-chondrite normalized rare earth element abundances for FANs 65325 and 60015, IMC, anorthositic regolith breccia meteorites, and 66095 clasts.

Results: Trace-element compositions of IMC contrast strongly with the FAN that they coat (*Figure 1*). FAN 65325 has the lowest rare earth element (REE) abundances and a large positive Eu anomaly, whereas FAN 60015 has relatively high REE abundances (~1 × CI-chondrite). In contrast, IMC have high REE abundances with a 'KREEPy' signature (LREE > HREE) and negative Eu anomalies. Anorthositic regolith breccia meteorite MIL 090036 has a similar 'KREEPy' signature to the IMC, whereas anorthostic regolith breccia meteorites MAC 88105, MIL 090034, MIL 090070 and MIL 090075 have lower REE abundances and positive Eu anomalies. Abundances of siderophile elements are highest in the IMC, with up to 1100 μg g^{-1} Ni (*Figure 2*). Tungsten contents are also highest in the IMC, and remarkably also in their host FAN.

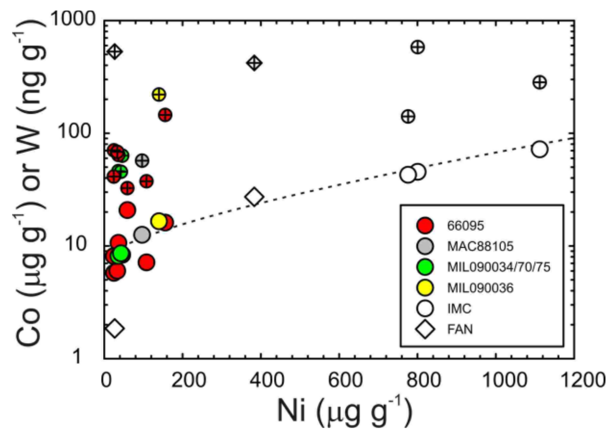

Figure 2: Ni versus Co and W (symbol with crosses) abundances for FAN (65325, 60015), IMC, lunar highland anorthositic regolith breccia meteorites, and clasts from IMB 66095.

To date, we have measured the abundances of the HSE (Os, Ir, Ru, Pt, Pd, Re) and Re-Os isotope systematics in four anorthositic regolith breccias (MIL 090034/36/70/75) and in IMB 66095. MIL 090036 has the highest HSE abundances, at abundances similar to some clasts of the IMB 66095 (*Figure 3*). Conversely, MIL 090034/70/75 have lower and more fractionated HSE patterns, with low Pd, Pt and, in one case, Ir. Clast fragments from IMB 66095 exhibit a range in absolute and relative abundances of the HSE, generally at the lower range of HSE abundances typically measured in IMB. Osmium isotope compositions of the anorthositic regolith breccias range between 0.1234 (MIL 090036) and 0.1245-0.1262 (MIL 090034/70/75). These values are at the lower end of present-day chondritic Os isotope compositions, overlapping most strongly with carbonaceous chondrites (e.g., [10]). Sample MIL 090036 plots close to the 4.5 Ga IIIAB iron meteorite isochron in ^{187}Re/^{188}Os-^{187}Os/^{188}Os space, but the fragments of MIL

090034/70/75 are consistent with much younger crystallization ages, as expected for regolith breccia materials. Rhenium-Os isotope systematics are disturbed in the fragments of 66095 that we analyzed.

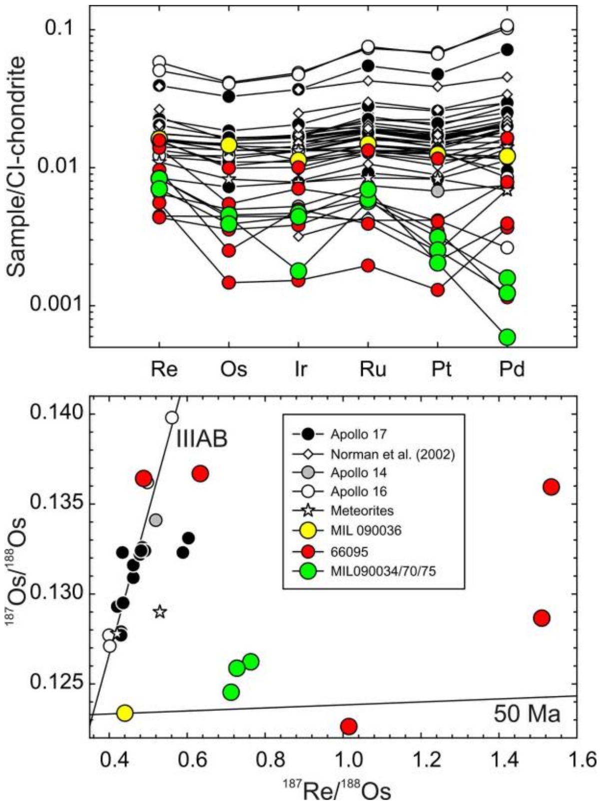

Figure 3: CI-chondrite normalized HSE abundance patterns (top) and $^{187}Re/^{188}Os$-$^{187}Os/^{188}Os$ plot (bottom) for IMB, and anorthositic regolith breccias. Shown is the 4.5Ga IIIAB isochron and a 50 Ma isochron tied to $^{187}Os/^{188}Os$ = 0.123. Published data are given in [10].

Discussion: *Origin of regolith breccia meteorites.* It has been shown that MIL 090036 is distinct from the other MIL (090034/70/75) anorthositic regolith breccia samples [11, 12]. Our new data support a lunar Procellarum KREEP terrane component for MIL 090036 [12], with high HSE abundances, similar to some IMB, and a KREEPy signature, similar to some IMC. Conversely, MIL 090034/70/75 have significantly lower and more fractionated HSE abundances and lower REE abundances. These samples have similar REE abundances to MAC 88105. Whether these samples originate from a farside lunar terrane [12], or not, the fractionated and low HSE abundances suggest less impact contamination than for MIL 090036 and possible fractionation of Pt and Pd from Os and Ru, by impact fractionation or volatilization processes.

Complexities in calculating impactor compositions. Lunar crustal samples collected during the Apollo program and as lunar meteorites contain both ample physical and geochemical evidence for impactor materials with generally chondritic and, in some cases, iron meteorite-like characteristics (e.g., [1, 2, 13-14]). Although data are limited, prior work has shown that IMC have similar HSE contents to IMB, but that the Os/Ir and Pd/Ir ratios for IMC are much closer to estimates for Earth's primitive mantle [3]. We previously suggested that these variations can be interpreted in two ways. First, IMC likely formed later than IMB and so reflect the addition of impactor material closer in composition to modern-day chondrites than the non-chondritic Pd/Ir of many IMB. Alternatively, the presence of sulfide-metal droplets in fast-cooled IMC indicate that larger, slower cooled impact melt sheets and IMB could have resulted in segregation of these phases (e.g., metal-rich rock 14286, 11 [15]). Since HSE have high affinity for FeNi metal/sulfide, the non-chondritic Pd/Ir ratios of IMB could reflect different incompatibilities of the HSE into segregated FeNi metal-sulfide phases. New data for the lunar anorthositic regolith breccias also suggest that the compositions of materials involved in the formation of IMB on the lunar surface can be compositionally quite complex and require fractionation processes acting at the lunar surface.

Plausible explanations for IMB formation include mixing between multiple, temporally distinct impactors striking the lunar crust, including mixing of chondritic and differentiated iron impactors, or fractionation of the HSE in melt-sheets. The high $^{187}Os/^{188}Os$ and Pt/Ir, Pd/Ir and Ru/Ir of some lunar crustal samples make them good candidates for mixing to explain IMB compositions [10]. Given the percentage of impactor additions to lunar impact melt rocks estimated from the HSE (<5%), and the low HSE abundances of lunar crustal materials, it would require enrichment of the endogenous HSE in the lunar crust, possibly described by an R-factor style process, involving scavenging of the HSE in FeNi metal and sulfides during impact melting, to explain relative mixing required for IMB.

References: [1] Norman et al. (2002) *EPSL*, 202, 217. [2] Puchtel et al. (2008) *GCA*, 72, 3022. [3] Jiskoot et al. (2014) *LPSC*, 45, 1332. [4] Warren & Wasson (1977) PLSC, 8th, 2215. [5] Day et al. (2010) *EPSL*, 289, 595. [6] Borg et al. (2011), *Nature*, 477, 70. [7] Day et al. (2016) *GGR*, 40, 49-65. [8] Day et al. (2017) *GCA*, 198, 379-395. [9] Day et al. (2016) *LPSC*, 47, 2516. [10] Day et al. (2016) *RIMG*, 81, 161. [11] Liu et al. (2011) LPSC, 42, 1261. [12] Calzada-Diaz et al. (2017) MAPS, 52, 3. [13] Korotev (1994) *GCA*, 58, 3931. [14] Fischer-Godde & Becker (2012) *GCA*, 77, 135. [15] Warren (2012) LPI, 9034.