THE COMPOSITION OF BASIN FORMING IMPACTORS AND LARGE-SCALE IMPACT GARDENING IN THE LUNAR HIGHLANDS. P. Gleißner[1] and H. Becker[1], [1]Freie Universität Berlin, Institut für Geologische Wissenschaften, Malteserstr. 74-100, 12249 Berlin, Germany (gleissner@zedat.fu-berlin.de).

Introduction: Material that accreted after planetary core formation may have influenced the composition (e.g., availability of volatiles like H, C, S) and later evolution of the terrestrial planets. Central questions are: Was the accreted material similar to known solar system objects like the meteorites in our collections? Was it rich or poor in volatile components? When was the material accreted and can we relate impactite compositions to specific impact events and/or basins?

Lunar impact basins and ancient impactites provide a valuable record of late accretion, starting from the formation of a solid crust until the onset of mare volcanism (~4.4 to ~3.6 Ga). However, the origin of variably fractionated HSE patterns in different lithologies and landing sites is still debated [1-7]. Here we discuss new data on highly siderophile element (HSE) abundances and $^{187}Os/^{188}Os$ ratios in lunar impactites together with previous data. The current dataset comprises now a variety of impact lithologies from different Apollo landing sites and two lunar meteorites. In addition we have obtained new data on siderophile volatile element (SVE) abundances in a subset of impactites. SVE may help to constrain the volatile content of impactors as well as reworking processes within the lunar crust.

Samples and methods: The current data set includes siderophile elements in KREEP-rich mafic impact melt rocks and breccias, KREEP-poor fragmental matrix breccias and granulitic impactites (Apollo 14, 15, 16 and 17 landing site). Osmium isotopes and HSE were determined after high pressure asher digestion in reverse aqua regia following the procedure of [3]. In addition, SVE like Cu, Ag, Te, Se, S, Cd and Tl were determined after digestion of other sample aliquots in HF-HNO_3 in Parr bombs, using separation techniques previously tested for terrestrial and extraterrestrial materials [14].

Results and discussion: A compilation of all published and unpublished data reveal that impactites from different landing sites display a broadly linear correlation of $^{187}Os/^{188}Os$ ratios and HSE/Ir ratios which range from sub- to suprachondritic (Fig. 1). The compositional range was interpreted to either reflect signatures of compositionally distinct basin forming primitive impactors, some of them outside the range of known chondrites [1, 2, 4, 5] or to result from variable mixing of several ancient impactor compositions [3, 6]. In order to better constrain the composition of accreted material we will discuss the different impact lithologies and adherent HSE patterns with respect to their crustal provenance and inferred time of formation.

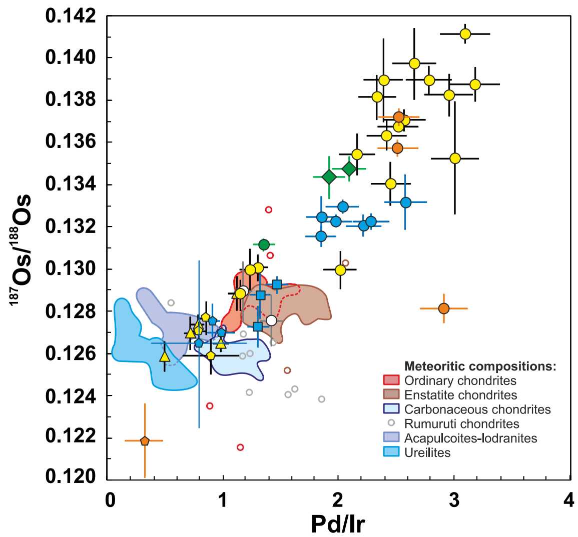

Fig. 1 HSE ratios in lunar impactites are shown with 2σ error bars [2-7]. The ranges of chondrite classes and primitive achondrite groups are given for comparison [8-12]. For colors of symbols see Fig. 2.

KREEP-rich mafic impactites. Most HSE data was obtained on KREEP-rich mafic impact melt rocks and breccias. Samples from four different landing sites display variably fractionated HSE patterns with suprachondritic Re/Os and HSE/Ir ratios increasing towards moderately volatile HSE like Pd and Au. Collectively these impactites display suprachondritic Ru/Pt ratios, a feature which is observed only in a limited number of differentiated metal-bearing meteorites. The widespread occurrence of this rather uncommon composition was interpreted as the result of accretion of larger fragments of differentiated planetesimal core material to a KREEP-rich target region [6]. Entrained clasts in Apollo 14 breccias display the latter signature. However, because the Imbrium impact only led to brecciation of these rocks [15], incorporation of the metal signature into the protolith of the breccias must have occurred during earlier impacts prior to formation of the Imbrium basin [7]. SVE abundances in different KREEP-rich impactites reveal mixing and homogenization with either, volatile-rich or –poor primitive impactor materials [7].

Granulitic impactites. Granulites are KREEP-poor impactites which mainly display recrystallization ages > 4 Ga. Hence, their HSE inventory is interpreted to reflect accretion of material to a KREEP-poor target region prior to formation of the younger impact basins, which apparently dominate the accessible ejecta deposits. The relative HSE abundances in Apollo 16 and 17 granulites are similar and strongly suggest accretion of volatile-depleted impactor material (possibly volatile-depleted carbonaceous chondrite or primitive achondrite-like).

Fragmental matrix breccias. This lithology is dominant at the North Ray Crater of the Apollo 16 landing site and is interpreted as representative of the Descartes formation. The HSE inventory of these breccias is characterized by diverse impactite clasts, including KREEP-rich mafic melt breccias and granulitic impactites. In contrast to other impact lithologies, fragmental matrix breccias preserved an impactor signature different from known primitive meteorites. The HSE inventory is characterized by moderate depletions in Re and Os when compared to Ir, Ru and Pt, but chondritic Re/Os and a gradual depletion towards moderately volatile Pd and Au. We interpret the latter signature as representing unknown primitive impactors with fractionations caused by nebular processes, like incomplete condensation or evaporation.

Large-scale impact gardening. Most studied KREEP-poor North Ray Crater breccias follow a linear mixing trend from slightly subchondritic HSE ratios towards the composition of HSE-rich and fractionated KREEP-rich impactites sampled in the Cayley formation and other Apollo landing sites (Fig. 1). This, together with the presence of KREEP-rich impactite clasts, comprising characteristically fractionated HSE, in breccias of different landing sites constrains physical mixing processes ranging from the scale of g-sized samples to the area covered by the Apollo missions. However, comparison of Pd/Ir ratios (as measure of HSE fractionation) with U abundances in impactites (i.e., the fraction of KREEP) reveal preservation of distinct compositional clusters at different landing sites (Fig. 2).

In Fig. 2, different samples and Apollo landing sites show variable proportions of the differentiated metal component (high Pd/Ir) relative to KREEP content. This, and systematic differences between some landing sites (e.g., Apollo 14, 15, 17, Fig. 1, 2) are best explained by early accretion of a core fragment onto the area of the Procellarum KREEP Terrane, variable mixing with KREEP-rich highland rocks and subsequent distribution of this combined signature and mixing with more primitive impactor material from KREEP poor sites. HSE and lithophile element compositions of granulitic impactites and fragmental matrix breccias reveal that material similar to carbonaceous chondrites and acapulcoite-lodranite primitive achondrites was accreted early onto KREEP-poor highland regions.

Summary: Material accreted during the formation of lunar basins comprises primitive and differentiated, metal-rich compositions. Signatures of primitive impactor material preserved in most impactites suggest volatile depleted carbonaceous chondrite-like or primitive achondrite-like impactor compositions. Some of the refractory element compositions are different from bulk chondrites and may reflect early fractionation processes in warmer domains of the solar nebula. The composition of most lunar impactites is consistent with mixture of several ancient impactor compositions due to large-scale impact gardening.

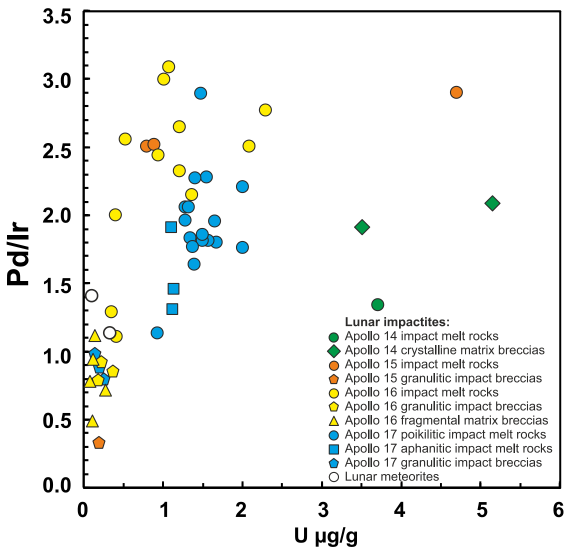

Fig. 2 Pd/Ir ratios vs. U abundance (proxy for KREEP) in lunar impactites. Compiled from [1-7] and [13].

References: [1] Norman M. D. et al. (2002) *EPSL 202*, 217-218. [2] Puchtel I. S. et al. (2008) *GCA 72*, 3022-3042. [3] Fischer-Gödde M. and Becker H. (2012) *GCA 77*, 135-156. [4] Sharp M. et al. (2014) *GCA 131*, 62-80. [5] Liu J. et al. (2015) *GCA 155*, 122-153. [6] Gleißner P. and Becker H. (2017) *GCA 200*, 1-24. [7] Gleißner P. and Becker H. submitted *GCA*. [8] Horan M. F. et al. (2003) *Chem. Geol. 196*, 27-42. [9] Fischer-Gödde M. et al. (2010) *GCA 74*, 356-379. [10] Van Acken D. et al. (2011) *GCA 75*, 4020-4036. [11] Rankenburg K. et al. (2008) *GCA 72*, 4642-4659. [12] Dhaliwal J. K. et al. (2017) *GCA 216*, 115-140. [13] The Lunar Sample Compendium (https://curator.jsc.nasa.gov/lunar/lsc). [14] Wang Z. et al (2015) *GGR 39*, 185-208. [15] Snape J. F. et al (2016) *GCA 174*, 13-29.

Acknowledgements: This work is funded by the Deutsche Forschungsgemeinschaft (Grant: Be1820/12-1, SFB-TRR 170, subproject B1). Samples were provided by NASA JSC and CAPTEM.