HIGHLY SIDEROPHILE ELEMENT CHARACTERISTICS OF LUNAR IMPACT MELT BRECCIAS: A PICTURE BEGINS TO EMERGE. R. J. Walker[1], O.B. James[2], D.A. Kring[3], J. Liu[4], M.G. Sharp[1], and I. S. Puchtel[1] - [1]Dept. of Geology, Univ. Maryland, College Park, MD 20742. rjwalker@umd.edu, [2]Emeritus US Geological Survey, Reston, VA 20192, [3]Lunar & Planetary Institute, Houston, TX 77058, [4]Dept. Earth & Atmos. Sci., Univ. Alberta, Edmonton, AB T6G 2E3

Introduction: It has long been hypothesized that the Earth-Moon system, and likely the entire inner solar system, underwent a phase of late accretion, termed *late heavy bombardment* (LHB), within the interval of time from ~4.1 to ~3.8 Ga [1-3]. Although the putative LHB had a major effect on shaping the surface of the Moon, it likely involved much less mass than is envisioned for late accretion as a whole. Even generous estimates for the mass of the LHB place the mass of materials involved as no more than about 10% of estimates for the overall mass of late accretionary additions. Nevertheless, the LHB may have delivered substantial water, and other volatile species, including organic molecules, to the Earth and Moon, so it is important to characterize the chemical nature of the materials involved.

The primary means to examine the chemical characteristics of materials from the LHB has been to analyze lunar impact melt rocks that were created as a result of the basin-forming impacts. The bulk of the highly siderophile elements (HSE: including Re, Os, Ir, Ru, Pt, and Pd) present in lunar impact-melt rocks were derived from meteoritic materials incorporated in the melt fraction. The relative abundances of the HSE in these rocks can provide diagnostic chemical fingerprints of the impactors because pristine lunar crustal rocks have extremely low concentrations of these elements [4], and possible impactors, such as chondrites and iron meorites have comparatively high abundances of these elements [5]. Several recent studies have utilized isotope dilution techniques to measure HSE concentrations and have also reported $^{187}Os/^{188}Os$ ratios, in order to characterize multiple pieces of a given melt rock. When the data for a given sample are collectively plotted, the slopes of the linear trends generated from plots of Ir versus other HSE, and $^{187}Os/^{188}Os$, define the relative abundances of HSE in the impactors associated with lunar basin formation [6-9].

There is now a sizable database for HSE present in impact melt rocks from Apollo 14, 15, 16 and 17 landing sites, as well as for several lunar meteorites. Comparison of data from the diverse locations provides a new way of considering the nature of late heavy bombardment to the Moon and Earth.

Discussion: In approximately half of the rocks examined, the results of plots of Ir versus each of the other HSE within each rock measured yield linear trends with intercepts indistinguishable from 0, within regression uncertainties. In such cases, the trends can be assumed to represent mixing trends between a single exogenous impactor and the HSE devoid lunar target rocks.

Puchtel et al. [6] and Sharp et al. [8] reported and interpreted data mainly for Apollo 17 impact melt rocks. Both studies reported a "dominant" component for the site, most notably characterized by suprachondritic Re/Os (as measured by $^{187}Os/^{188}Os$), Ru/Ir, Pt/Ir and Pd/Ir, comparable to the results from Norman et al. [10]. They interpreted the results to suggest that the dominant source of HSE to the site, most likely the Serenitatis basin impactor, shared broad similarities to some chondritic meteorites (enstatite chondrites), but sampling a composition not presently found in our meteorite collections. A distinct, feldspar-rich component in some of these rocks as well as in other lunar impact melt rocks, termed *granulite*, was found to be characterized by relative abundances of HSE more similar to ordinary chondrites.

Fischer-Gödde and Becker [7] focused most of their attention on impact melt rocks from the Apollo 16 site. Here they found HSE ratios extending much higher than known chondrites, and even well beyond the range of the Apollo 17 rocks. They also analyzed some granulitic rocks and reported, like prior studies, that this component (or components) is most like ordinary chondrites. Of note, the study recognized that virtually all of the HSE data for Apollo samples (i.e., among multiple rocks) form linear trends when plotting Ir versus other HSE or $^{187}Os/^{188}Os$. They interpreted this to mean that all of the Apollo impact melt rocks incorporated two major 2 HSE-rich components at the time of their formation. One was very similar to ordinary chondrites, and is the major component in granulitic rocks. The other component most resembles a chemically evolved group IVA iron meteorite. Consequently, they proposed that both components became variably mixing during basin forming impacts, but were not substantially modified by HSE derived from the basin-forming impactors that created the rocks.

Most recently Liu et al. [9] reported considerable additional data for Apollo 15 and 16 impact melt rocks, continuing to note, as with [7], that all lunar data plot along what appears to be continuous linear trends ranging from a composition that is similar to ordinary chondrites, to an endmember with $^{187}Os/^{188}Os$, Ru/Ir and Pd/Ir ratios far above those of known chondrites. All of the existing data plotted in **Figure 1a-c**.

Possible scenarios to explain the observed trends include: 1) Variable mixing between an earlier granulitic contaminant(s) with chondritic HSE and a series of impactors that happen to have co-linear, suprachondritic Re/Os, Ru/Ir, Pt/Ir and Pd/Ir. 2) Variable mixing between earlier granulitic contaminant(s) and a series of metallic impactors related by crystal-liquid fractionation, resulting in variably suprachondritic Re/Os, Ru/Ir, Pt/Ir and Pd/Ir. 3) Variable mixing between an earlier impactor contaminant in the crust characterized by fractionated HSE abundances (e.g., fractionated metal), and a series of impactors with chondritic HSE that led to creation of the basins. 4) Variable mixing between two components present in the lunar crust prior to the last basin forming impacts. One component (or suite of components) was chondritic in composition, the other component had fractionated HSE, and could have been an isolated core fragment (this is the model of [7]). At this time, these models cannot be discriminated and await genetic testing using nucleosynthetic anomalies characteristic of some siderophile elements.

References: [1] Turner G. et al. (1973) *Proc. 4th Lunar Sci. Conf.*, 1889-1914. [2] Tera F. et al. (1974) *EPSL*, *22*, 1-21. [3] Spudis P. D. and Ryder G. (1981) *Proc. Lunar Planet. Sci. Conf. 12A*, 133-148. [4] Day J. M. et al. (2010) *EPSL 289*, 595-605. [5] Horan M. F. et al. (2003) *Chem. Geol.* 196, 5-20. [6] Puchtel I. S. et al. (2008) *GCA*, *72*, 3022-3042. [7] Fischer-Gödde M. & Becker H. (2012) *GCA 77*, 135-156. [8] Sharp M. et al. (2014) GCA 131, 62-80 [9] Liu J. et al. (in review) *GCA*. [10] Norman M. D. et al. (2002) *EPSL 202*, 217-228. [11] Walker R.J. et al. (2002) GCA 66, 4187- 4201. [12] Horan M.F. et al. (2003) *Chem. Geol. 196*, 5-20. [13] Fischer-Gödde et al. (2010) *GCA 74*, 356-379 [14] McCoy T.J. et al. (2011) *GCA 75*, 6821-6843.

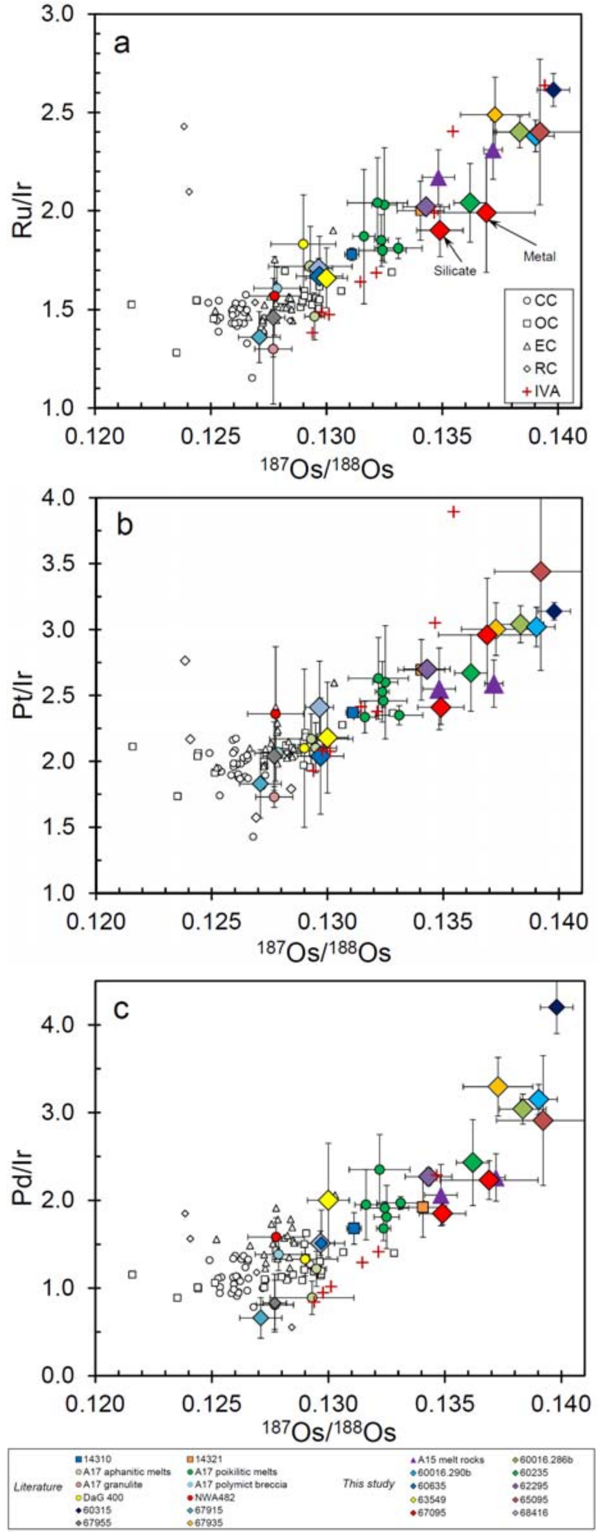

Figure 1a-c. Average $^{187}Os/^{188}Os$ *vs.* Ru/Ir (a), Pt/Ir (b), and Pd/Ir (c) for the impactor components incorporated in the lunar impact melt rocks examined here and in the literature, in comparison with ratios of chondrites (gray symbols), and IVA iron meteorites (red crosses). Lunar data are from references [6-9]. Data sources for chondrites are from references [11-13] and for IVA iron meteorites are from [14]. Figures are from [9].