

**HIGHLY SIDEROPHILE ELEMENTS IN THE EARTH, MOON, AND MARS: UPDATE AND IMPLICATIONS FOR PLANETARY ACCRETION AND DIFFERENTIATION.** R.J. Walker<sup>1</sup>, I.S. Puchtel<sup>1</sup>, J.D. Day<sup>1</sup>, A.D. Brandon<sup>2</sup>, O.B. James<sup>3</sup> and L. Loudin<sup>4</sup>. <sup>1</sup>Department of Geology, University of Maryland, College Park, MD 20742 ([rjwalker@geol.umd.edu](mailto:rjwalker@geol.umd.edu)), <sup>2</sup>NASA, JSC, Houston, TX 77058, USA, <sup>3</sup>U.S. Geological Survey, 926A National Center, Reston, VA 20192, <sup>4</sup>Keene State College, Keene, NH 03431

**Introduction.** The highly siderophile elements (HSE) include Re, Os, Ir, Ru, Pt and Pd. These elements are initially nearly-quantitatively stripped to some extent from planetary silicate mantles during core segregation. They then may be re-enriched in mantles via continued accretion upon cessation of further core segregation. Processes that include metal-silicate segregation at high P and T the base of a magma ocean [1], and late accretion have been touted as the dominant controls on HSE abundances in planetary mantles [2]. Thus, depending on the dominant process, this suite of elements and its included long-lived radiogenic isotopes systems ( $^{187}\text{Re} \rightarrow ^{187}\text{Os}$ ;  $^{190}\text{Pt} \rightarrow ^{186}\text{Os}$ ) might either be used to constrain the depth of metal-silicate segregation, or to “fingerprint” the characteristics of late accreted materials. If the latter, the fingerprints may ultimately be useful to constrain the prior nebular history of late accreted materials, and to compare the proportion and genesis of late accretionary materials added to the inner planets.

The past ten years have seen considerable accumulation of isotopic and compositional data for HSE present in the Earth’s mantle, the lunar mantle and lunar impact melt breccias, as well as martian meteorites. Here we review some of these data and consider the broader implications of the compiled data.

**Earth.** Studies of the Os isotopic compositions of terrestrial peridotites that have been long isolated from convection in the upper mantle (e.g. ancient subcontinental lithospheric mantle) have led to the conclusion that the inferred  $^{187}\text{Os}/^{188}\text{Os}$  of Earth’s Primitive Upper Mantle (PUM) matches that of enstatite/ordinary chondrites, not the more volatile rich carbonaceous chondrites [3].

Recent attempts to constrain the absolute and relative HSE budget of the PUM have led to recognition that there are some discrepancies between the relative abundances of these elements in the PUM and chondrites. For various suites of peridotites (including continental mantle, orogenic lherzolites and abyssal peridotites), HSE were correlated with melt depletion/enrichment indicators and extrapolated to an estimate of the PUM [4]. For most HSE, abundances in PUM are similar to earlier estimates. However, estimates of Ru/Ir and Pd/Ir derived from most suites indicates modestly suprachondritic compositions for average PUM. This has been observed by other groups as well [5-6], although the effects of melt depletion can now be

discounted. Thus, although HSE in the terrestrial PUM can be placed in a broad “chondritic” family, it is not a perfect match to any one chondrite group that exists in our collections. This can be interpreted in one of several ways. First, if the HSE were established by late accretion, the dominant late accreted materials may have had a somewhat different nebular history compared to the chondrites in our collections. This would not be surprising. Nebular, and perhaps subsequent processing on parent bodies has been shown to result in considerable fractionation of HSE. Second, the deviation from chondritic ratios could be an indication that processes other than, or in addition to late accretion controlled HSE abundances in the mantle. For example, many workers have experimentally explored the possibility that the comparatively high abundances of HSE in the mantle are a result of relatively low metal-silicate bulk partitioning at the base of a deep magma ocean. Recent studies have demonstrated that Re, Pd, Pt and Au may have sufficiently low D values at magma ocean conditions to explain their mantle abundances [7-9]. This is an unlikely explanation for Re and Os, given the close adherence of  $^{187}\text{Os}/^{188}\text{Os}$  and  $^{186}\text{Os}/^{188}\text{Os}$  to chondritic (which allows us to constrain Re/Os and Pt/Os in the PUM better than any other HSE ratios). Retention of precisely chondritic Pt/Re/Os is an unlikely result of metal-silicate partitioning. Nonetheless, this possibility begs future experimental consideration. Retention of excess Ru and Pd in the silicate Earth following metal segregation, relative to other HSE, could result in suprachondritic ratios involving these elements, allowing the possibility of a hybrid model for generating HSE abundances. Finally, it may be that mantle processes (melt removal & refertilization, crustal recycling) have complicated the HSE budget of the mantle beyond our current capability to deconvolute them and obtain an accurate estimate of the PUM.

**Moon.** There are currently no known samples of the lunar mantle in our collections, so HSE abundances in the lunar mantle must be estimated from derivative melts. This is non trivial. Most prior studies of HSE in lunar volcanic rocks have reported relatively low concentrations of HSE, such as Ir, in lunar basalts and picritic glasses [10-12]. Relative to terrestrial rocks with comparable MgO contents, the lunar mantle sources of these rocks appear to be depleted in the HSE by at least a factor of 20 (**Fig. 1**). This observation may indicate that the lunar mantle did not receive a late accretionary component like that suggested to

explain the HSE budget of Earth's mantle. The "missing" HSE could reside in a late-formed lunar core. However, because metal segregation would likely lead to strong fractionation of Re from Os in the silicate mantle, the approximately chondritic initial  $^{187}\text{Os}/^{188}\text{Os}$  ratios of lunar basalts weighs against this possibility [11-12]. Alternately, the low abundances could indicate that either late accretion was not the dominant process controlling HSE in the terrestrial mantle (and so, the Moon), or that late accretion preceded formation of the Moon. The chondritic Re/Os of the PUM is problematic for the former interpretation, yet the latter possibility is also difficult to envision, given the likelihood HSE stripping of the mantle during the putative giant impact that created the Moon.

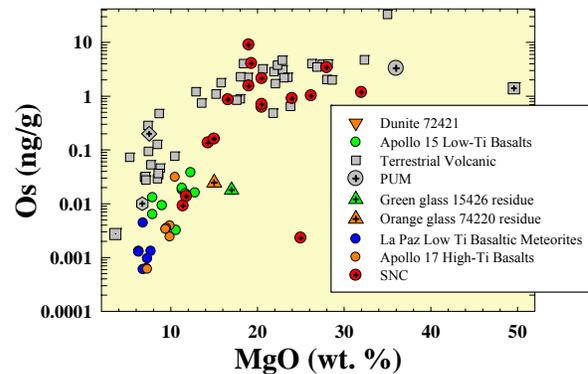
Potentially direct information regarding the chemical nature of late accreted materials to the Earth-Moon system can be obtained by examining the HSE contained in lunar impact-melt rocks. Our work on lunar impact melt rocks indicates that at least some of the impactors that created the lunar basins had relative abundances of the HSE outside of the range of chondrites currently sampled by Earth [13] (Fig. 2). This may mean that the supra chondritic Ru/Ir and Pd/Ir of the PUM can be accommodated by a late accretion model that is dominated by materials with HSE characteristics slightly outside of the range of known chondrite groups.

**Mars.** Re-Os studies of SNC meteorites indicate that the martian mantle evolved with a dominantly chondritic Re/Os [14]. HSE measurements for SNC meteorites are broadly consistent with derivation from mantle sources bearing HSE concentrations similar to those present in the terrestrial upper mantle (Fig. 1). The HSE abundances and chondritic Re/Os of SNC meteorites suggest that, if established by late accretion, the martian mantle received a proportionally similar mass of late accreted materials as was added to Earth. This would be somewhat surprising given that final core segregation may have occurred 10s of Ma apart for the two planets. Consequently, a similar bombardment flux would have to be either coincidence, or the result of dominantly later stage events that may have substantially postdated final core segregation. If instead the HSE abundances in both the terrestrial and martian mantle were established primarily by lowered D values under magma ocean conditions, D values were remarkably similar for both planets.

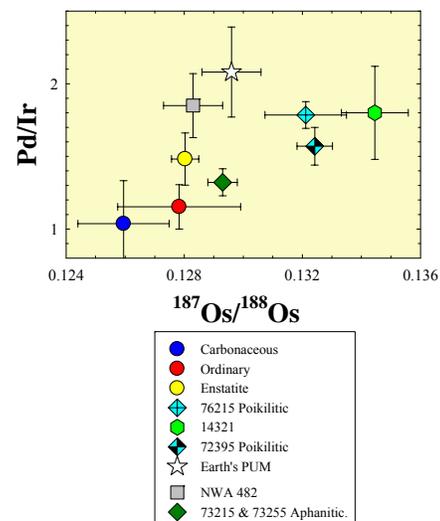
**References.** [1] Murthy (1991) *Science* **253**, 303. [2] Chou (1978) *Proc. 9<sup>th</sup> Lunar Planet. Sci. Conf.*, 219. [3] Meisel et al. (2001) *Geochim. Cosmochim Acta* **65**, 1311. [4] Becker et al. (2006) *Geochim. Cosmochim Acta* **70**, 4528. [5] Patou et al. (1996) *Nature* **379**, 712. [6] Schmidt (2004) *Met. Planet. Sci.* **39**, 1995. [7]

Richter & Drake (1997) *Earth Planet. Sci. Lett.* **146**, 541 [8] Cottrell & Walker (2006) *Geochim. Cosmochim Acta* **70**, 1565. [9] Richter et al. (2008) *Nature Geosci.* doi:10.1038/ngeo180 [10] Warren et al. (1989) *Earth Planet. Sci. Lett.* **91**, 245 [11] Walker et al. (2004) *EPSL* **224**, 399 [12] Day et al. (2007) *Science* **315**, 270 [13] Puchtel et al (2008) *Geochim. Cosmochim Acta* **72**, 3002 [14] Brandon et al. (2000) *Geochim. Cosmochim Acta* **64**, 4083 [15] Walker et al. (1999) *Geochim. Cosmochim Acta* **63**, 713.

**Acknowledgements.** This work was supported by NASA grants NNG04GJ49A and NNX07AM29G.



**Fig. 1.** Plot of Os concentrations (ng/g) versus MgO for lunar, SNC and terrestrial volcanic rocks. Most lunar data are offset significantly below the terrestrial array, suggesting that abundances of the highly siderophile elements in the lunar mantle are substantially lower than in the terrestrial mantle. Terrestrial data are from the literature but are mostly from the Caribbean Large Igneous Province [15]. Lunar data are from [11-12]. Data for most SNC [14] are similar to terrestrial.



**Fig. 2.** Plot of Pd/Ir versus  $^{187}\text{Os}/^{188}\text{Os}$  (a proxy for Re/Os) for lunar impact melt rocks. Shown for comparison are the range of compositions for chondritic meteorites, and estimates of Earth's primitive upper mantle. Data are from [3,13].