ABUNDANCES OF HIGHLY SIDEROPHILE ELEMENTS IN DIOGENITES COMPARED WITH THE MANTLES OF EARTH, MARS AND THE MOON: CONSISTENT WITH STOCHASTIC LATE ACCRETION?

R. J. Walker[1], J. M. D. Day[1,2], W. F. Bottke[3], L. T. Elkins-Tanton[4], D. Nesvorny[3], A. J. Irving[5]. [1]Univ. Maryland, College Park, MD 20742 rjwalker@umd.edu; [2]Scripps Inst. Ocean., La Jolla, CA 92093; [3]Southwest Res. Inst., 1050 Walnut St., Boulder, CO 80302; [4]MIT, Cambridge, MA 02139; [5]Univ. Washington, Seattle, WA 98195

Introduction: The highly siderophile elements (HSE) are normally strongly partitioned into iron metal relative to silicates, yet the abundances of these elements estimated for Earth's primitive upper mantle (PUM) and the martian mantle are only about 200 times lower than those of bulk chondrites [1-4]. These abundances are considerably higher than would be expected from low P-T metal-silicate partitioning [5-6]. Establishment of their abundances via metal-silicate partitioning at the bases of transient magma oceans has been proposed to account for their abundances, given that the siderophilic nature of some HSE is greatly reduced under high P-T conditions [7-8]. The generally chondritic relative abundances of HSE, however, suggest that this was not the dominant process, given the apparent great range of metal-silicate D values among the HSE at elevated P-T [9], as well as the similarity in abundances between terrestrial and martian mantles [4].

Continued accretion after final core segregation, or *late accretion*, is currently the most robust hypothesis to account for the absolute and relative HSE abundances in the terrestrial and martian mantles [10]. Such a process is consistent with chondritic relative abundances, as all HSE from the late accreted impactors are added to the mantle. Further, addition of 0.4 to 1% of additional mass to Earth and Mars following cessation of core segregation is permitted by current dynamical models of planetary accretion. Yet, despite the appealing aspects of the late accretion hypothesis, the apparently substantially lower HSE abundances in the lunar mantle (~20 ×) [11], compared to the terrestrial mantle, pose a severe problem for the late accretion hypothesis [4]. Even when accounting for a smaller cross section and a much weaker gravitational field, the Moon would be expected to have similar HSE concentrations in its mantle compared to Earth.

In a recent paper [12], we proposed *stochastic late accretion* as a possible solution to this problem. Stochastic late accretion draws late-stage impactor bodies largely from a population dominated by massive bodies. Using Monte Carlo models, we found that the relative HSE abundances in terrestrial, martian and lunar mantles could be reasonably accounted for if the late accretion population had the form $dN \propto D^{-q}\, dD$ (i.e., dN is the number of planetesimals of diameter D within bin dD), and the power law index of the projectiles was $q < 2$ for $200 < D < 4000$ km. A limited number of large, random impacts gives the Earth and Mars a significantly higher probability of being hit by large bodies than the Moon. Here, the largest impactors striking the Earth are in the 2500 to 3000 km diameter range, whereas the Moon was struck by a maximum of 250 to 300 km diameter bodies [12]. This hypothesis assumes that the late accretionary period for the Earth and Moon began immediately following the putative giant impact that created the Moon at ~50-100 Ma after Solar System formation, and that the Moon-forming event was the last global clearing of HSE from the terrestrial mantle into its metallic core. To allow late accreted materials to enter the lunar mantle and become mixed, materials would have to have been added prior to substantial crust formation, or of sufficient size to breach the crust. Late accretion to Mars may have been dominated by earlier impacts, given the very early cessation of its core segregation 7 to 15 Ma after CAI formation [13].

An important question is how to apply these ideas to the interpretation of the HSE signatures of differentiated asteroids like Vesta, which may also have been affected by late accretion. The early bombardment history of these small worlds was likely different from that of Earth, Moon, or Mars. Issues to consider include: (i) Vesta and its brethren are smaller targets than Earth/Moon/Mars, such that the largest early impactors to strike them may have been $D < 100$ km; (ii) if the inner main asteroid belt is any guide, the planetesimal size distribution in the inner solar system was steep for $100 < D < 250$ km projectiles and shallow for $D < 100$ km; (iii) Vesta and other differentiated objects formed magma oceans within the first few Ma of solar system history through radioactive decay, much earlier than Mars and the Moon that formed magma oceans through late giant impacts; (iv) The starting location of these worlds is unknown; For example, Vesta might have formed in the terrestrial planet region, where it was subject to a different impactor flux [14].

Further tests of the stochastic late accretion hypothesis are warranted, yet there are limited data applicable to the consideration of other bodies. The most likely candidates for mantle materials of other differentiated bodies are some diogenite meteorites, presumed to come from Vesta or related objects. Here we consider the HSE abundances of diogenites within the framework of stochastic late accretion.

Methods: In the last two years we have reported HSE abundance and $^{187}Os/^{188}Os$ for diogenites [15-16]. Data were obtained using our standard methods [17]. Because of the possibility of small-scale, late-stage contamination of HSE by the impacts that liberated samples from the parent body, we used a split-sampling method to assess the degree of heterogeneity within diogenite whole-rocks. This method has been successfully used to constrain levels of meteoritic contamination within lunar crustal rocks [17]. Triplicate analyses of samples by Carius Tube (CT) and High Pressure Asher (HPA) digestions indicate that the HSE are generally evenly distributed within individual samples.

Discussion: Chronologic evidence for eucrites and diogenites suggest early formation of Vesta and rapid differentiation and crystallization [e.g., 13]. Thus, post-differentiation accretion to Vesta would have begun earlier than to Mars, and much earlier compared to Earth and the Moon. Although some samples are brecciated and possibly contain late-stage chondritic contaminants, many of the samples show no signs of such contamination and probably reflect *bona fide* HSE abundances for the mantle of the parent body [16]. This interpretation is consistent with the general homogeneity of HSE within individual meteorites. If it is assumed that the HSE characteristics of most diogenites are reflections of processes internal to Vesta, then their generally chondritic natures, most notably reflected in chondritic $^{187}Os/^{188}Os$, suggests chondritic additions following core formation, but prior to completion of mantle crystallization [15-16].

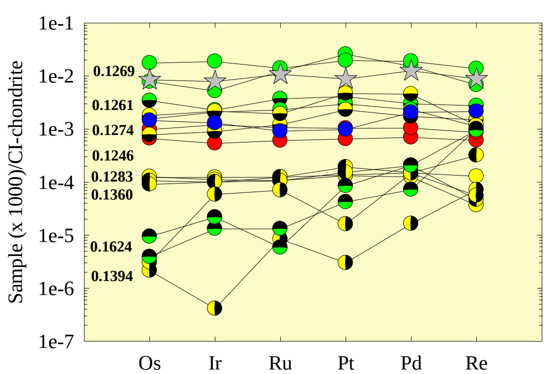

Figure 1. *HSE abundances for orthopyroxenitic and harzburgitic diogenites, normalized to CI chondrites. Also included are $^{187}Os/^{188}Os$ ratios for each sample (from [16]). Pattern delineated by gray stars is Earth's primitive upper mantle for comparison.*

The high degree of variation in concentrations indicates a graininess to the late accretionary process that was not mixed out by mantle convection, as might be expected to result from a short lived magma ocean phase with limited chemical mixing in such a small body [18]. The distinctly non-chondritic abundances of samples with low overall HSE abundances, including suprachondritic $^{187}Os/^{188}Os$ reflect either post-core formation domains in the mantle with minor or no subsequent late accretion, or evidence that these rocks include cumulate components.

If our interpretation of stochastic late accretion is valid, we can consider different alternatives. Perhaps only a portion of the Vesta was affected by late accretion (e.g., a large basin-formation event at ~4.5 Ga; [19-20]), such that some HSE signatures are more consistent with regional rather than global effects. The diogenites dredged up to the surface by this event may have experienced different levels of HSE contamination.

Models of melting planetesimals through radioactive decay indicates that only planetesimals reaching tens of km in radius before 1.5 Ma after CAI formation are able to melt internally and fully differentiate (see references in [21]). Recent modeling [21] further indicates that significant later additions are likely to these bodies, including material that is incompletely mixed into the differentiated silicate body, and which retains its original chondritic signature. Planetesimals like Vesta, therefore, may be expected to retain compositional heterogeneity that records their magnitude and frequency of late accretion.

References: [1] Ringwood A. E. (1966) *GCA 30*, 41-104. [2] Morgan J. W. et a.l (1981) *Tectonophys. 75*, 47-67. [3] Mitchell R. H. and Keays R. R. (1981) *GCA 45*, 2425-2445. [4] Walker R. J. (2009) *Chem. Erde 69*, 101-125. [5] Kimura K. et al. (1974) *GCA 38*, 683-781. [6] O'Neill H. et al. (1995) *Chem Geol. 120*, 255-273. [7] Murthy V. (1991) *Science 253*, 303-306. [8] Cottrell E. and Walker D. (2006) *GCA 70*, 1565-1580. [9] Brenan J. and McDonough W. F. (2009) *Nature Geosci. 2*, 798-801. [10] Chou C-L. (1978) *Proc. Lunar Planet. Sci. Conf. 9th*, 219-230. [11] Day J. M. D. et al. (2007) *Science 315*, 217-219. [12] Bottke W. F. et al. (2010) *Science 330*, 1527-1530. [13] Kleine et al. (2004) *GCA 68*, 2935-2946. Bottke, W. F. et al. (2006) *Nature 439*, 821-824. [15] Day J. M. D. et al. (2009) LPSC 40th abstract #1992; [16] Day J. M. D. et al. (2010) *LPSC 41st*, abstract #1942 [17] Day J. M. D. et al. (2010) *EPSL 289*, 595-604. [18] Elkins-Tanton et al. (2008) *LPSC 39th* abstract #1364. [19] Bogard D. and Garrison D. (2003) *MAPS 38*, 669. [20] Li J.-Y. et al. (2010) *Icarus 208*, 238-251. [20] Elkins-Tanton et al. (2011) *EPSL*, submitted.