# COMPARATIVE PLANETOLOGY OF THE HIGHLY SIDEROPHILE ELEMENTS: IMPLICATIONS FOR THE ACCRETION OF THE TERRESTRIAL PLANETS.

J.H. Jones[1], C.R. Neal[2], and J.C. Ely[2], [1]Mail Code: SR, NASA Johnson Space Center, Houston, TX 77058, [2]Dept. Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556 (jjones2@ems.jsc.nasa.gov).

The abundances of the highly siderophile elements (HSE) in the mantles of the terrestrial planets are of great importance in deciphering the accretion and differentiation of bodies of the inner solar system [1,2]. For the Earth in particular, the HSE appear to be in chondritic relative proportions [3]. In addition, the absolute abundances of the HSE are depleted relative to chondrites (~0.007 X CI; [3]), but much less than would be predicted on the basis of metal-silicate equilibrium [1]. Measured HSE affinities for Fe-Ni metal are $~10^5$-$10^8$ larger than their affinities for silicate (e.g., [1]; whence the denotation *highly siderophile*); and actual HSE affinities for metal are possibly $~10^4$ larger than those that have actually been measured [4]. Because of these observations, it is currently believed that the HSE were added to the Earth as a "late veneer" of chondritic material subsequent to core formation [3]. And recently, several researchers have suggested that the same may be true for the Moon [2] and Mars [5, 6]. Here we explore the implications of new HSE data for the Moon and Mars and suggest that special circumstances would be required to make these data compatible with the late veneer hypothesis.

**Earth.** For the Earth, there is a large and growing body of data that supports and confirms earlier inferences (e.g., [7]) of chondritic relative abundances of HSE in the Earth's mantle [3]. In this regard, xenoliths from the sub-continental lithosphere and massif peridotites are especially important. Because we have direct samples from the Earth's mantle, we do not need to reconstruct terrestrial HSE abundances using analyses of mantle-derived basalts or need to precisely know how HSE fractionate during basalt genesis. Unfortunately, we have no samples of the mantles of the Moon and Mars, so we must rely on inferences from basalts.
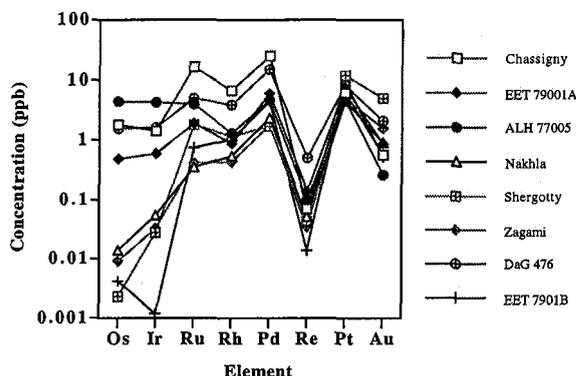
**Mars.** Figure 1 shows a plot of our preferred values for HSE in SNC meteorites, a suite of rocks from the planet Mars [8]. Some elements like Os and Ir vary greatly between meteorites ($10^3$-$10^4$ X variation), whereas other elements, especially Pt, vary much less. Platinum in the SNC meteorites averages 6.2 ± 3.1 ppb (0.0063 X CI) — a constancy that is remarkable, considering the difficulties of sampling, contamination, and analysis.

This surprising lack of variation implies that Pt acts indifferently during basalt petrogenesis with a bulk partition coefficient (D) of near unity. This inference is reinforced by the observation that the SNC meteorites comprise a very diverse suite of lithologies (e.g., [9]): Chassigny is a cumulate dunite; ALH 77005 is a cumulate lherzolite; EET79001A is a basalt

with harzburgitic xenoliths; Nakhla is a cumulate clinopyroxenite; EET79001B is an evolved basalt; Dar al Gani (DaG) 476 is a basalt with cumulus olivine; and Shergotty and Zagami are moderately evolved basalts containing cumulus pyroxene. Again, the simplest way to explain the constancy of Pt is if $D^{Pt}$ is ~1, a result that is consistent with the terrestrial dataset. For example, Puchtel and Humayun, in modeling the petrogenesis of komatiites, used a bulk D(Pt) of 0.5 [10].
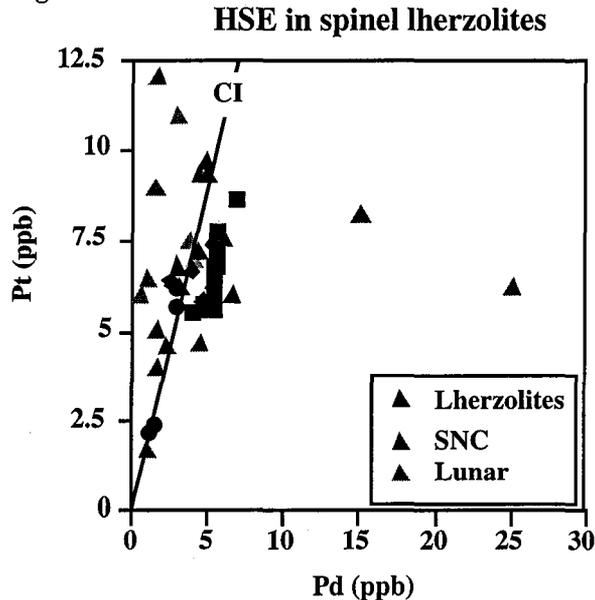
It is difficult to compare HSE between the SNC suite and terrestrial basalts, because the latter have often experienced sulfide fractionation. However, a recent study by [11] of East Greenland basalts (unaffected by sulfide fractionation) indicates that both primitive (Mg# ~60) and evolved (Mg# ~ 43) compositions have Pt concentrations of 5-10 ppb, much like the SNC suite.

**Figure 1**

**Highly Siderophile Elements in SNC Meteorites**



A corollary of $D^{Pt}$ ~1 is that the Pt concentrations of the SNC meteorites are close to that of bulk silicate Mars. Consequently, it is interesting to compare the Earth and Mars. Figure 2 is a plot of Pt vs. Pd for SNC meteorites and fertile spinel lherzolites from the Earth's mantle [12, 13, 14, 15]. [In Figure 2 all black symbols represent terrestrial lherzolites, regardless of the shape of the symbol.] Palladium is not a perfect proxy for Pt and shows more variation than Pt within the SNC suite (Figure 1). Nonetheless, there is a large overlap between the SNC's and terrestrial lherzolites; and both suites cluster about the line defined by the chondritic Pt/Pd ratio. Note that, unlike most diagrams involving siderophile elements, the axes are linear. It appears that the mean Pt concentration for bulk silicate Mars is very similar to, if not the same as, that of the Earth's upper mantle. The average Pt abundance for

**Figure 2**



**HSE in spinel lherzolites**

the abundance for the lherzolites in Figure 2 is 6.5 ± 0.8 ppb. This is identical, within error to that of the SNC suite. If a chondritic late veneer is responsible for the HSE abundances in the silicate portions of the Earth and Mars, then the process acted extremely similarly on both planets.

**Moon.** Platinum abundances for the Earth and Mars become more interesting if the Moon is also considered. Figure 2 includes analyses of several low-Ti lunar basalts [16]. Platinum data for lunar rocks is quite limited. Nevertheless, the range of Pt abundances is not large, with the lunar average being 7.7 ± 1.6 ppb (including two analyses from [17]). We suggest, given the current uncertainties in sampling and in *exactly* how Pt behaves geochemically, that the Pt contents of the silicate portions of the Earth, Moon, and Mars should be viewed as indistinguishable. There is also the inference, made previously by others [2, 3, 6], that the HSE in the bulk silicate portions of these planets may be in chondritic relative proportions. This seems clearly true for the Earth (e.g., Figure 2) and may also be true for the Moon and Mars. Of course, if the Moon and Mars received their HSE *via* a late veneer, then they should have chondritic relative proportions of these elements, by definition.

**Discussion.** But there is little reason to suspect that a late veneer of asteroidal or cometary impactors should constitute the same proportion of three different planets, of different sizes and distances from the sun [18]. The Earth and Moon should see approximately the same flux of these postulated impactors, but Mars presumably did not, being at a different heliocentric distance. Conversely, if the Earth and Moon were subjected to the same flux of impactors, the Moon should have ~4X more of this material than the Earth. Oversimplifying, both bodies will accumulate impacts

in proportion to their planetary cross section (~$r^2$) but this material will be diluted throughout their interiors in proportion to their planetary volumes (~$r^3$). Regardless of the ultimate source of the late veneer material, these considerations still apply.

Thus, there may be cause to re-evaluate the notion that a late veneer was responsible for adding HSE to the mantles of the terrestrial planets. There has always been the vexing issue of how such material was so thoroughly homogenized in the Earth by such an early date [1]. Now there is also the issue of why the proportion added was seemingly everywhere the same. We have no real explanation for this observation, except to note that such constancy seems unlikely to be produced by an external process, such as a late veneer [3], or perhaps even by an internal process, such as inefficient core formation [1]. Neither process seems capable of producing HSE abundances that are constant from planet to planet. Thus, we seek a mechanism that essentially buffers HSE abundances at slightly less than one percent of their chondritic values, regardless of planetary size or exact geologic history.

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