MODERATELY VOLATILE ELEMENTS IN LUNAR AND MARTIAN METEORITES; WHAT DIFFERENCES DO THEY REVEAL BETWEEN LUNAR AND MARTIAN VOLATILE ELEMENT INVENTORIES? Burney, D.[1], Neal, C.R.[1], and Day, J.M.D.[2]. [1]University of Notre Dame, Notre Dame IN, 46556; dburney@nd.edu. [2]Scripps Institution of Oceanography, University of California San Diego, La Jolla CA 92093-0244, USA

Introduction: Moderately Volatile Elements (MVEs) are defined as elements with a solar nebula 50% condensation temperature between 650 and 1350 K and include Zn, Se, Rb, Ag, Cd, In, Sb, Tl, Pb, and Bi [1,2]. The recent quantification of highly volatile species (H_2O, CO_x, F, Cl, and S) in lunar materials has prompted new investigations into the loss or retention of volatiles during the formation and evolution of the Moon [3-5]. The MVEs with their more intermediate condensation temperatures potentially allow them to record catastrophic fractionation events. As the Moon differentiated and evolved through a magma ocean, the generally incompatible MVEs remained in the surrounding melt and partially recorded degassing event(s) that occurred [6]. The crystalization of the lunar magma ocean (LMO) produced the source regions for the mare basalts. The early phases to crystallize out of the LMO were predominantly olivine followed by orthopyroxene (e.g., [7]). Titanium became progressively enriched in the residual melt eventually producing ilmenite ($FeTiO_3$) [7]. Ilmenite increased the density of the late-stage cumulates, which subsequently induced an overturn of the LMO cumulate pile [7,8]. The last dregs of the LMO were highly enriched in incompatible elements such as K, REE, and P (ur-KREEP) [9]. Partial melting of the early LMO cumulates, late LMO cumulates, and ur-KREEP produced low-Ti mare basalts, High-Ti basalts, and KREEP basalts, respectively [9,10].

Generally, assuming no outgassing, the MVEs would be continually enriched in the residual melt throughout LMO crystallization. Therefore, predictions can be made: low-Ti mare basalts should contain the lowest concentrations increasing progressively through the high-Ti mare and KREEP basalts. The data reported here for the mare basalts shows that MVEs in low-Ti and high-Ti mare basalts are at similar concentrations (**Figs. 1 & 2**). The exception to this are the elements Se and Ag, the most chalcophile of the MVEs. For these two elements a distinct enrichment is seen in the high-Ti basalts relative to the low-Ti basalts (**Fig. 2**). These two compositional trends are interpreted to result from degassing events (crust-breeching impact(s); cf. [11]) that effected the LMO after formation of the low-Ti basalt source(s), but did not effect the concentrations of Se and Ag. Recent experimental constraints on the sulfur concentration at sulfur saturation (SCSS) has shown that several of the high-Ti basalts have a whole-rock sulfur content to be considered sulfur saturated [12,13]. The formation of sulfides in the high-Ti basalt source region may have sequestered Se and Ag that were later exhausted during mare basalt partial melting.

Mars is a more complicated case than for the Moon due to its larger size (and, therefore, heat engine) and protracted evolution. While Mars is a more volatile-rich body than the Moon, heterogeneities within different martian reservoirs have been identified from martian meteorites, which are generally classified as Shergottites (basalts), Nahklites (pyroxene cumulates, or Chassignites (olivine cumulates) (SNC meteorites [14]). Shergottites have been further subdivided based on trace element composition as enriched, intermediate, or depleted (e.g., [15]). All of these meteorites are considered to be partial melts from a differentiated source [15]. Nakhlites are comprised mostly of augite [14,15]. The sample ALH84001 is an orthopyroxenite and is the oldest of the SNC meteorites [16]. Mars is, therefore, assumed to also be more enriched in the MVEs relative to the Moon. This assumption is supported by available MVE data (e.g., Zn) for the SNC meteorites. This work explores if such an enrichement is consistent across the suite of MVEs, and if the different types of Shergottite can be identified using the MVEs using newly acquired MVE data for martian and lunar meteorites..

Methods: Homogenized powders of martian and lunar meteorites were digested using HF and HNO_3 and analyzed via solution mode inductively coupled plasma mass spectrometry (ICP-MS). No HCl was used to limit Cl polyatomic interferences as well as MVEs forming

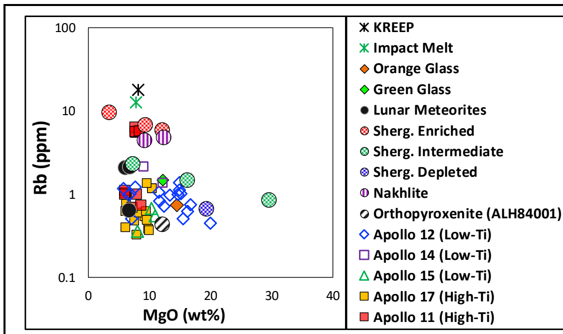

***Figure 1**: MgO vs Rb. The Shergottite classification of enriched, intermediate, and depleted correlates with Rb content. While one lunar meteorite is comparable to low-Ti Apollo samples, two are higher which may represent terrestrial contamination.*

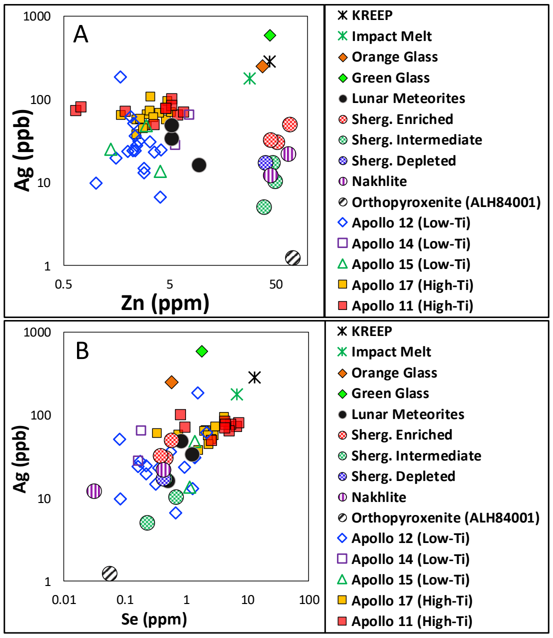

***Figure 2**: (A) Zn vs Ag and (B) Se vs Ag. While the Martian meteorites roughly follow the established classification with respect to Ag, Zn and Se shows a fairly uniform concentration. The orthopyroxenite is the most depleted in Ag, but shows Zn concentrations far above lunar levels.*

volatile chloride species that could be lost during digestion. Polyatomic interferences were quantified and corrected for using a method outlined in [17,18]. Standard reference materials BIR-1 and BHVO-2 were analyzed with the meteorites to monitor accuracy and precision of data.

Results and Discussion: There is significant overlap between lunar and martian samples with respect to MgO content (**Fig. 1**). Charactarization of MVE separates samples into distinct groupings (e.g., [14,15]). In **Fig. 1**, Rb concentrations mimic the Shergottite classification of enriched, intermediate, and depleted having the highest to lowest concentrations, respectively. The Rb concentration in orthopyroxenite ALH 84001 is the lowest of the martian samples, but is comparable to many of the lunar basalts (**Fig. 1**). Nakhlites are comprised of mostly augite, and exhibit Rb concentrations that are between the enriched and intermediate shergottites (**Fig. 1**). The lunar meteorites are all low-Ti basalts and should be similar to the Apollo 12, 14 and 15 mare basalts (open symbols). The Rb concentrations in one lunar meteorite is similar to that seen in low-Ti basalts, but two are distinctly higher (**Fig. 1**). This may be the result of terrestrial contamination for these two samples. While terrestrial contamination has been observed, often as interstitial veins, the lunar meteorites allow for a direct comparison between pristine samples that were collected on the Moon, with those that arrived via impact processes and were exposed to the terrestrial environment.

A comparison of Zn vs. Ag for martian meteorites shows that although variation can be seen in some trace elements (Ag), others are more homogenous (Zn) (**Fig. 2A**). With respect to Ag, the shergottite meteorites reflect the traditional classification although the depleted sample reflects a more intermediate composition (**Fig. 2A**). The nakhlites fall roughly between the intermediate and enriched shergottites, and ALH84001 is the most depleted sample (**Fig. 2A**). For Se, there is large overlap between the SNC meteorite compositions and the distinction between the shergottite types is not as apparent. (Fig. 2B). All martian meteorites plot with the low-Ti mare basalts with respect Ag and Se (**Fig. 2B**). The lunar meteorites are similar to low-Ti basalt compositions in both plots (**Fig. 2A&B**), except for Zn where two samples fall within the high end of the low-Ti basalt field, and one lies distinctly above (**Fig. 2A**).

Conclusion: The martian meteorites follow the current classification of enriched, intermediate, or depleted with respect to the MVEs (e.g., Ag and Rb) but other elements do not (e.g. Zn and Se). While Mars is more enriched in volatiles relative to the Moon, there is no uniform enrichment of MVEs. We interpret this to reflect the more complicated/dynamic geologic evolution of Mars with respect to the Moon.

The lunar meteorites allow for a direct comparison of pristine samples to those that have been delivered through impact processes and exposed to terrestrial contamination. The lunar meteorites are classified as low-Ti basalts and generally mimic the behavior of those Apollo samples, although there are enrichments seen in the meteorites that may be indicators of terrestrial contamination.

References: [1] Palme, H. et al. (1988) *Meteorites and the Early Solar System 1*, 436-461. [2] Lodders, K. (2003) *The Astrophysical Journal 591*(2), 1220. [3] Hauri E. et al. (2011) *Science 333*, 213-215. [4] McCubbin F. et al. (2015) *Amer. Mineral. 100*, 1668-1707. [5] Saal A. et al. (2008) *Nature 454*, 192-195. [6] Dhaliwal, J.K. et al. (2018) *Icarus 300*, 249-260 [7] Elkins-Tanton, L.T. et al. (2011) *EPSL 304*, 326-336. [8] Spera F.J. (1992) GCA 56, 2253-2265. [9] Warren P.H. (1985) AREPS 13, 201-240; [10] Hallis, L.J. et al. (2014) *GCA 134*, 289-316. [11] Barnes J. et al. (2016) EPSL 447, 84-94. [12] Ding, S. et al. (2018) *GCA* 222, 319-339. [13] Steenstra, E.S. et al. (2018) *GCA 231*, 130-156. [14] McSween, H.Y. (1994) *Meteoritics 29(6)*, 757-779. [15] Day, J.M.D. et al. (2018) *Nat. Comm. :4799*. [16] Borg L.E. et al. (1999) LPSC XXX #1430. [17] Burney, D.C. et al. (2017) *LPSC 48*, #1068. [18] Burney D.C. and Neal C.R. (2019) JAAS (under review).