

ASSESSMENT OF A HIGH-ENERGY ORIGIN OF THE MOON FROM METAL-SILICATE PARTITIONING OF SIDEROPHILE ELEMENTS AT HIGH TEMPERATURES. E.S. Steenstra^{1,2}, Y. Fei², S. Matveev³, J. Berndt⁴, S. Klemme⁴, W. van Westrenen¹ ¹Faculty of Science, Vrije Universiteit Amsterdam, the Netherlands ²The Geophysical Laboratory, Carnegie Institution of Science, Washington D.C., USA ³Faculty of Geoscience, Utrecht University, the Netherlands ⁴Institute of Mineralogy, Muenster University, Germany

Introduction: Constraints on the thermal regime during lunar core-mantle differentiation are of great importance for lunar chemical and thermal evolution models and provide boundary conditions for lunar formation models [1-3]. It is now well established that the vast majority of both volatile and refractory siderophile elements are depleted in the lunar mantle relative to bulk silicate Earth (BSE), suggesting these elements partitioned into the lunar core [4-8]. Previous studies have shown that the metal-silicate partitioning behavior of Ni, Co, Cr and V is mainly a function of fO_2 , pressure (P), temperature (T) and metal composition [9-13]. Increasing geochemical evidence points to highly similar compositions of the bulk Moon and the BSE [3,14]. Assuming that the Ni, Co, Cr and V budget of the BSE is representative of the bulk Moon, Ni and Co behave far too siderophile at low T (i.e. along the mantle liquidus), relative to the inferred lunar mantle depletions [9-13,15-19]. At these same conditions, V and Cr behave insufficiently siderophile. Different fO_2 during lunar core formation cannot resolve this discrepancy because it will affect all four elements in a similar way. Although S in metal decreases the siderophile behavior of Ni, Co and increases the iron-loving tendencies of V, Cr [12,19], recent studies on S abundances in the lunar mantle in conjunction with mass balance models have indicated that the lunar core is S-poor [5,20-22].

Current lunar formation models predict that T during and shortly after the Moon-forming impact ranged anywhere between >3000–7000 K [1-2,23-25]. Lunar core formation at very high T may therefore be reflected by the unique lunar mantle depletion patterns of Ni, Co, Cr, V, as hypothesized by ref. [6]. This latter hypothesis should also be consistent with the observation that Mn is not depleted in the lunar mantle relative to BSE [16]. To test this hypothesis, high P - T experiments were conducted using a primitive lunar silicate melt to systematically study the effects of T on the metal-silicate partitioning behavior of many siderophile elements, including Ni, Co, Cr, V, and Mn. These new results can be compared with our previous partitioning results obtained at lower T using the same capsule type and starting compositions [8,12,26].

Methods: High P - T experiments were performed in a 1500-ton multi-anvil apparatus at the Geophysical Laboratory, using 18mm edge length Cr-doped MgO or ZrO₂ octahedra. Outer ZrO₂ sleeves were used as ther-

mal insulators in the MgO+Cr assemblies. All experiments were conducted at 4 GPa between 1973 – 2873 K at 100 K intervals. All experiments were conducted using C heaters, MgO spacers and 1 or 1.6 mm I.D. MgO capsules. Temperatures were measured up to 2473 K with a type C thermocouple and higher run T were constrained by linearly extrapolating well defined T – power curves obtained at 4 GPa. Starting compositions consisted of a synthetic equivalent of the A15 green glass [27] and Fe powder doped with several trace elements including Ni, Co, Cr, V and Mn. Run times varied between 15 min at 1873 K to 20s at 2873 K, which has been shown to be sufficient for metal-silicate equilibrium [28,29]. Polished experimental run products were analysed using EPMA at the Geophysical Laboratory and Utrecht University.

Results: Fig. 1 shows an example of a typical run product. Experiments yielded significant amounts of magnesiowustite crystals and substantial MgO enrichment of the silicate melt consistent with previous work [28,29]. These enrichments resulted in compositions that are similar to inferred bulk silicate Moon compositions [e.g. 2,5]. The fO_2 of the various runs are very similar and close to the lunar fO_2 range.

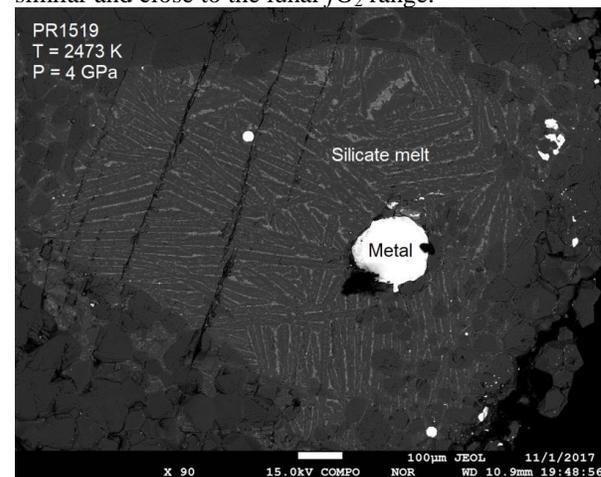


Fig. 1 BSE image of a typical run product.

Metal-silicate partitioning data was treated by consideration of the equilibrium constant K_{app} [9]:

$$\log K_{app} = \log \frac{(x_{FeO}^{silicate})^{n/2} \cdot (x_M^{metal})}{(x_{MO_{n/2}}^{silicate}) \cdot (x_{Fe}^{metal})^{n/2}} + \log \frac{(y_M^{metal})}{(y_{Fe}^{metal})^{n/2}} + \log \frac{(y_{FeO}^{silicate})^{n/2}}{(y_{MO_{n/2}}^{silicate})}$$

where the first term on the right-hand side is the exchange coefficient or K_M^D . The second and third terms relate to the activity coefficients of $M(O_{n/2})$ and $Fe(O)$. Activity coefficients were calculated using the metal activity calculator [13].

Fig. 2 shows preliminary $\log K_{app}$, Mn, Cr, Co values for the A15 green glass composition of this study and our previous work obtained at 1-2.5 GPa, as a function of T . The K_{app} values of Cr and Mn increase strongly with T , whereas those for Co decrease with T . These trends are in agreement with previous work [e.g. 11,13]. Different MgO contents cannot account for the dependency of K_{app} Cr and Mn on T , as experiments with overlapping silicate melt MgO contents still yield an increase with T . For Co, such conclusions cannot be drawn as of yet due to lack of data.

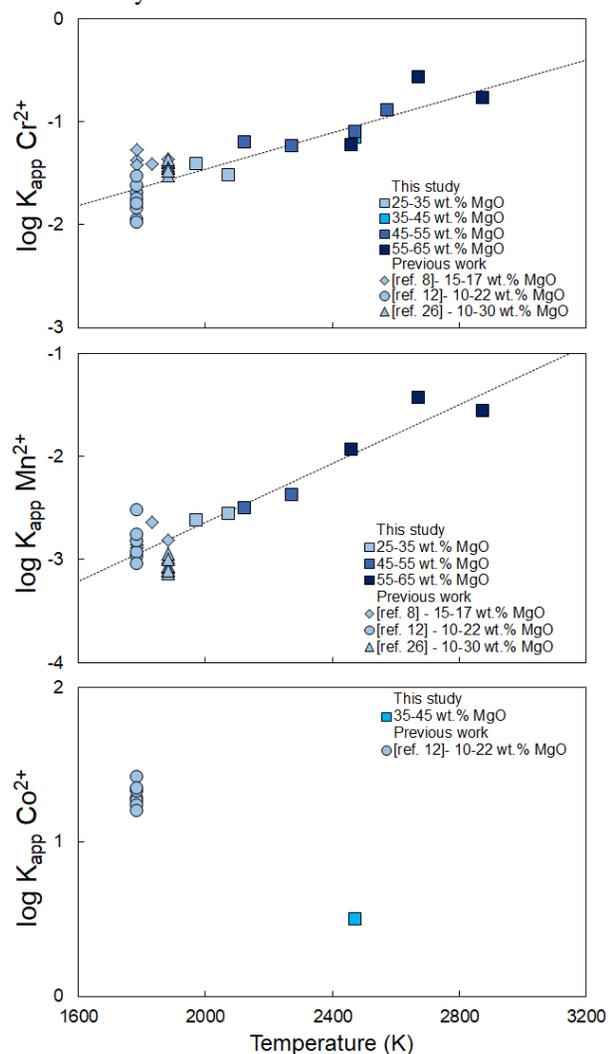


Fig. 2 K_{app} values from this study (squares) and previous work (obtained at 1-2.5 GPa) as a function of T . Also indicated are the relative MgO contents of each experiment. Lines are linear fits through data of this study only.

Finally, we found no dependency of fO_2 with T , consistent with previous work [30].

Discussion: Our preliminary results show that T indeed significantly increases the siderophile behavior of Cr, Mn. In conjunction with the negative T effects on partitioning of Co (and likely Ni), the lunar mantle depletion systematics may suggest high- T core formation in the Moon, providing tangible evidence for a giant-impact origin of the Moon. This can be fully assessed once additional analytical results are available.

Outlook: We aim to reconcile these results with new high- T data for volatile siderophile elements (VSE) at constant P . Additional experiments are currently being analysed and their results will be reported at the meeting, as well as trace element concentrations which will be measured using LA-ICP-MS at Muenster University, Germany.

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