

**CONSTRAINTS ON THE FORMATION OF A LUNAR CORE FROM METAL-SILICATE PARTITIONING OF SIDEROPHILE ELEMENTS** N. Rai and W. van Westrenen. Faculty of Earth and Life Sciences, VU University Amsterdam, The Netherlands (n.raai@vu.nl).

**Introduction:** In the currently prevailing model for the formation of the Earth-Moon system, the Moon formed as a byproduct of a giant impact between a Mars-sized planetesimal and the proto-Earth. Ejected material, mainly originating from the impactor, accreted in orbit around the Earth to form the Moon. One consequence of this high-energy process was the occurrence of extensive melting on the Earth and Moon, which would have led to planetary-scale differentiation on the young Moon. As on Earth, such differentiation could have led to the formation of a metallic core on the Moon. Most models for the interior of the Moon include a relatively small iron-rich core, having a radius between 200 and 450 km [1,2]. A recent study [3] based on the reanalysis of Apollo lunar seismograms using advanced array-processing methods to search for the presence of reflected and converted seismic energy from the core, suggests the presence of a solid inner and fluid outer core, overlain by a partially molten silicate layer in the lower mantle. The precise composition, formation conditions, and thermal evolution through time of the lunar core are not well constrained at present.

One major consequence of core-mantle differentiation in planetary bodies is that the majority of the siderophile elements are strongly partitioned into the iron-rich metallic core. Since the degree of extraction of these elements into metallic phases is governed according to their metal/silicate partition coefficients ( $D$ ) and the pressure-temperature-composition conditions during core formation, abundances of these elements in the silicate Moon can in principle be used to constrain lunar core formation conditions and composition [2,4,5]. Here we re-examine whether a consistent set of lunar core formation conditions can be obtained to match observed siderophile element depletions in the silicate Moon based on recent improvements in our understanding of siderophile element partitioning.

**Approach:** Estimates of siderophile element abundances in the lunar mantle have previously been used to argue for the presence of a small metallic core (0.1-5.5 wt%) [2,4,5], but recent improved approaches developed to constrain terrestrial core formation models (including better thermodynamic models and the ability to model changing conditions through time) have not been applied to the Moon to date. Figure 1 shows observed levels of bulk lunar silicate depletion for siderophile elements, based on values from [5,6,7]. We combine recently published metal-silicate partitioning data for Ni, Co, Cr, Mn, Ga, P, Pb, W and V with literature data [8-19] and characterize the dependence of

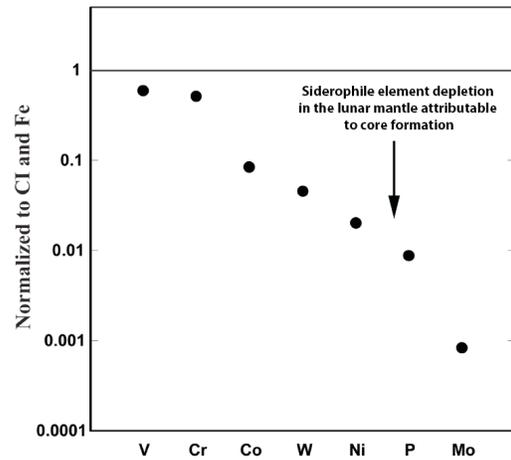


Figure 1. Estimated siderophile element depletion in the lunar mantle, based on refs. [5,6,7].

the partition coefficients ( $D$ ) on temperature, pressure, oxygen fugacity and silicate melt structure and composition to derive equations of the following form:

$$\log D = \alpha + \beta(\Delta IW) + \delta(1/T) + \epsilon(P/T) + \chi(\text{nbo}/t) \quad (1)$$

It is well established that trace elements in metal alloys strongly interact with major components such as Fe, Si, C and S, causing metal-silicate partitioning experiments performed under different compositional conditions to produce scattered results. Using a thermodynamic approach [13], all metal-silicate partitioning data used in this modelling work were corrected to a common reference point which is the effective value for a trace component mixing in pure metallic element in the liquid state. All partitioning data was parameterized according to Equation (1). For each element, only statistically valid regression coefficients were considered to model the conditions of lunar core formation. Our parametrizations are based on partitioning data obtained at pressures between 1 atm and 6 GPa, covering the range of pressures in the Moon. There is a hot and ongoing debate about the question whether metal-silicate partition coefficients show different behaviour at low pressure (< 5 GPa) compared to pressures above 5 GPa [20-22]. By using data obtained at pressures that are relevant to the Moon only ( $P < 6$  GPa) our results will be directly applicable to the Moon regardless of the final outcome of this debate. Using these parameterizations and the proposed bulk Moon composition of [4], we model core formation in the Moon.

**Results:** Pressure-temperature solution spaces that would produce metal-silicate partition coefficients matching the observed depletion of these elements in the lunar mantle were calculated for each element at changing conditions of oxygen fugacity according to the following relation derived from Equation (1):

$$P = (T/\varepsilon) * [\log D - \alpha - \beta(\Delta IW) - \chi(nbo/t) - \delta(1/T)] \quad (2)$$

Figure 2 shows the resulting overlap in P-T solution space for Ni, Co, W, P, and Mo in the pressure range of 3.5 - 4 GPa and temperature between 2100-2200 K at IW-1.5 and nbo/t = 2.8, assuming a pure Fe core.

However, under these conditions, we did not find

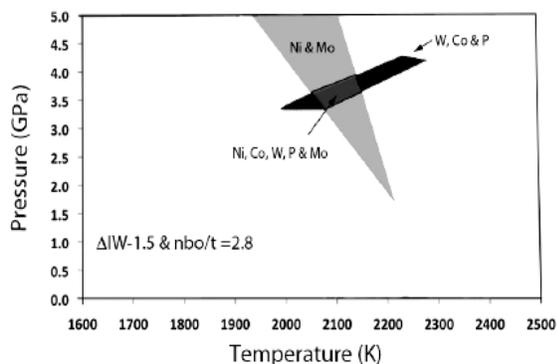


Figure 2: Overlap in the solution spaces for Ni, Co, W, P and Mo in the pressure range 3.5 - 4 GPa and between 2100-2200 K at IW-1.5 and nbo/t = 2.8, assuming pure Fe metal.

any overlap between the solution spaces of the weakly siderophile elements V and Cr with those for Ni, Co, W, P and Mo. Both V and Cr show lithophile behavior at these oxidation conditions (Figure 3). At the more reducing conditions where V and Cr become siderophile enough to account for their observed mantle depletion, other elements such as Ni, Co, W, P and Mo become much more depleted than observed.

**Discussion:** Our initial results suggest that when using the proposed bulk Moon composition of [4] and siderophile element abundances from [5,6,7], metal-silicate partitioning data for Ni, Co, W, P and Mo are consistent with the Moon possessing a small pure iron metallic core, with metal-silicate equilibration pressures close to the pressure at the current core-mantle boundary. As the pressure of equilibration obtained from analyses like these is generally taken as the approximate pressure at the bottom of a silicate magma ocean, this result would suggest the Moon was fully molten at the time of core formation.

**Outlook:** Seismic models of the Moon [3, 24] support the presence of up to 6 weight% of a lighter alloy-

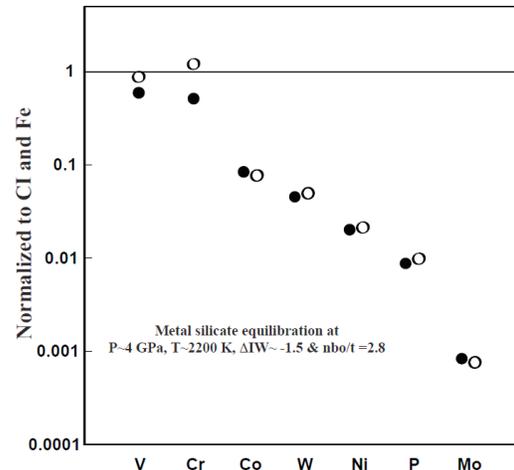


Figure 3: Solid symbols show the estimated element depletion in the lunar mantle. Depletion in Ni, Co, W, P and Mo can be accounted for by metal-silicate equilibration at P~4 GPa, T~2200 K, ΔIW~-1.5 and nbo/t = 2.8. Under these conditions V and Cr remain lithophile (open symbols).

ing element such as sulphur in the lunar core and recent analyses of lunar melt inclusions [23] indicate that realistic lunar interior evolution models should also consider the constraints imposed by the presence of H<sub>2</sub>O. Future work will include incorporation of the effects of light elements in the metal and the presence of water in the silicate on our results.

**References:** [1] Weiczorek et al. (2006) *Rev. Mineral. Geochem.*, 60, 221-364 [2] Righter and Drake (1996) *Icarus*, 124, 513-529 [3] Weber et al. (2011) *Science*, 331, 309-312 [4] O'Neill (1991) *GCA*, 55, 1135-1157 [5] Walter et al. (2000) In *Origin of the Earth and Moon*, U of A Press, Tucson, 265-289 [6] Newsom and Bessera (1990) *LPSC XXI*, 875-876 [7] Newsom and Runcorn (1991) *LPSC XXII*, 973-974 [8] Thibault & Walter (1995) *GCA*, 59, 991-1002 [9] Li & Agee, (1996) *GCA*, 65, 1821-1832 [10] Walter & Thibault (1996) *Science*, 270, 1186-1189 [11] Jana & Walker (1997) *EPSL*, 150, 463-472 [12] Chabot and Agee (2003) *GCA*, 67, 2077-2091 [13] Wade and Wood, (2005) *EPSL*, 236, 78-95 [14] Kegler et al., (2008) *EPSL*, 268, 28-40 [15] Wood et al., (2008) *GCA*, 72, 1415-1426 [16] Corgne et al. (2009) *GCA*, 72, 574-589 [17] Cottrell et al. (2009) *EPSL*, 281, 275-287 [18] Mann et al. (2009) *GCA*, 73, 7360-7386 [19] Siebert et al. (2011) *GCA*, 75, 1451-1489 [20] Righter et al. (2011) *EPSL*, 304, 158-167 [21] Palme et al. (2011) *EPSL*, 312, 516-518 [22] Sanloup et al. (2011) *EPSL*, 306, 118-122 [23] Hauri et al. (2011) *Science*, 333, 213-215 [24] Garcia et al. (2011) *EPSL*, 188, 96-113