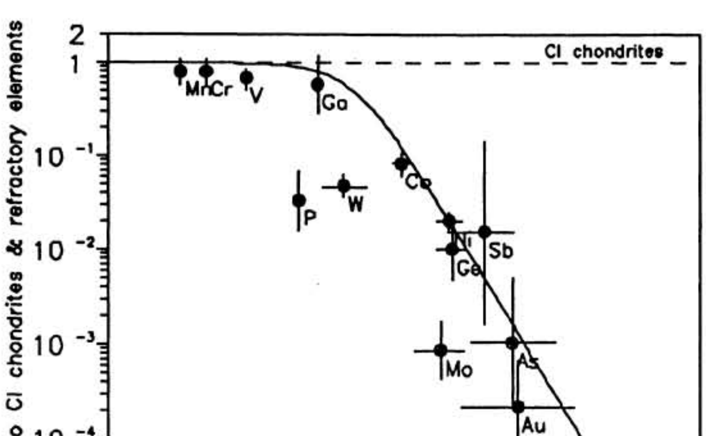
CORE FORMATION IN THE MOON: THE MYSTERY OF THE EXCESS DEPLETION OF Mo, W AND P; H.E. Newsom and S.A. Maehr, Institute of Meteoritics and Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM 87131

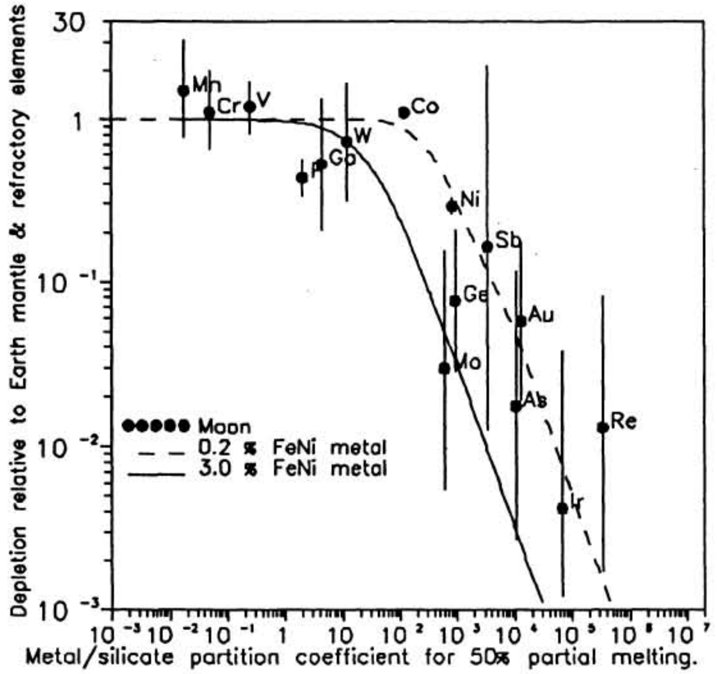
We have evaluated siderophile element depletion models for the Moon in light of our improved statistical treatment of siderophile element abundance data and new information on the physics of core formation. If core formation occurred in the Moon at the large degrees of partial melting necessary for metal segregation, according to recent estimates [1], then a significant inconsistency (not seen in the eucrite parent body) exists in the depletion of the incompatible siderophile elements Mo, W and P, compared to other siderophile elements in the Moon. The siderophile data, with the exception of Mo, are most consistent with terrestrial initial siderophile abundances and segregation of a very small core (<1 wt%) in the Moon. Our improved abundance estimates and possible explanations for these discrepancies are discussed below.

We have begun a recalculating the depletions of siderophile elements in the Earth and Moon using an improved statistical approach that takes into account the log normal behavior of siderophile element to lithophile element ratios. Preliminary results for depletions relative to CI and refractory elements are: for W in the Moon, mean 0.047, high 0.064, low 0.035, for Mo in the Moon, mean 0.00087, high 0.0018, low 0.00043, for W in the Earth, mean 0.0026, high 0.0057, low 0.0012, for Mo in the Earth, mean 0.029, high 0.045, low 0.019.

During core formation siderophile elements are depleted in the residual silicates of a parent body. Important factors controlling the pattern of siderophile element depletion include the amount of metal and the metal to silicate-melt partition coefficients. Another important factor [2] is the degree of partial melting during metal segregation, which is quantitatively controlled by the silicate-mineral to silicate-melt partition coefficients. The mineral/melt partitioning behavior for the siderophile elements varies drastically, from Ni and Co, which are strongly compatible, to elements, such as Ge, which are not strongly fractionated by mineral/melt partitioning, to W and Mo which are very incompatible. Because the behavior of these elements have an opposite dependence on the degree of partial melting, during a core formation event there will be a unique degree of partial melting for which the observed depletions of the different siderophile elements will be consistent with the same metal content.



In the case of the Moon, Newsom [3,4] showed that a smooth dependence of depletion versus metal to bulk-silicate partition coefficient only occurs for very low degrees of partial melting (5% to 10%). Recent results on the physics of metal segregation [1], however, strongly indicate that a much higher degree of partial melting, 50% or greater is needed to allow small amounts of metal to segregate from solid silicates. The problem is that metal does not wet silicates, at least at the low pressures in the Moon, and there is a finite yield strength that must be overcome for the metal to separate. Metal segregation at high degrees of partial melting is supported by the siderophile element modeling for the Eucrite Parent Body [5], which is consistent with metal segregation between 20% and 70% partial melting. If core formation in the Moon is assumed to have occurred at 50% partial melting (Fig. 1), than the observed depletions for W, Mo and P are too large, by a factor of 10 for a chondritic initial Moon. If terrestrial mantle initial abundances are assumed (Fig. 2), then the depletions of W and P may be compatible with the other siderophile elements within a factor of two, but Mo is still too depleted, by a factor of almost ten. Several possibilities can be discussed.



1. W and Mo are volatile under oxidizing conditions, as seen in large depletions of several orders of magnitude in some CAI's from carbonaceous chondrites [6]. In general, however, cosmochemical fractionations of W and Mo relative to refractory siderophile and lithophile elements are surprisingly small compared to the siderophile element depletions in samples from differentiated bodies. For example, the Mo/Ce ratio in carbonaceous chondrites only ranges up to 25% greater than the CI ratio (which is the wrong direction). The LL ordinary chondrites do have a lower Mo/Ce ratio than CI's, but only by less than a factor of 2. An additional problem with this explanation is that there is no evidence of a significant oxidized component on the Moon.

2. Uncertainties in partition coefficients can probably be ruled out because a factor of ten difference for Mo would be needed. The metal/silicate partition coefficients for W, Mo, Co and Ni have been checked by several groups. Although some problems have arisen regarding the results for Co and Ni, all of the investigations are in agreement for the conditions used in the modeling (1300 ℃, log fO_2=-12.6). The metal/silicate partition coefficients for some of the other elements, such as As, Sb, and the highly siderophile elements, cannot be trusted. The mineral/melt behavior of these elements is reasonably well established through experimental work and element correlations, except possibly for the behavior of Mo in the Moon.

3. Siderophile element abundances in the Moon and the Earth (a possible initial component) are well known for Ni, Co, W and Mo in the Earth, and for W in the Moon. The lunar depletion for Mo is based on less than a dozen analyses for only a few sites and could be incorrect. Additional data is also needed to check the variability of siderophile elements in different lunar reservoirs and sample sites, Ge for example is enriched in Apollo 14 samples compared to other Apollo sites [7], and variability in the abundances of P have been observed. The estimated Ni and Co abundances could be too low, if significant olivine fractionation has occurred, but this would make the discrepancy even worse. Supporting the data for Co and Ni are the depletion data for other siderophile elements, especially Ga, Ge, As, Sb and Au.

Conclusions- The currently available data and siderophile element depletion modelling suggest that for 50% partial melting during metal segregation, a better fit, with the exception of Mo, is seen for terrestrial initial abundances than for chondritic. A metal content for the Moon as large as 2-5 wt% is highly unlikely for terrestrial initial abundances. These results continue to emphasize the critical need to determine the size of the lunar core by geophysical methods. There is no obvious answer to the excess depletion problem for W, Mo and P in the Moon. However, significant progress can be made in better determination of the abundances of many siderophile elements in the Moon and their metal/silicate partition coefficients. If improved data for the other siderophile elements, such as Ga, Ge, As, Sb, and Au continue to be consistent with Co and Ni, in contrast to the data for Mo and W, a much stronger case could be made for a connection with Earth mantle initial abundances in the Moon, and for a very small lunar metal core (< 1 wt%).

References: [1] Taylor (1992) JGR Planets 97, 14,717. [2] Newsom and Drake (1982) Nature 287, 210. [3] Newsom (1984) EOS 65, 396. [4] Newsom (1986) Origin of Moon p. 203. [5] Hewins and Newsom (1988) In Meteorites and the Early Solar System 73. [6] Fegley and Palme (1985) Earth and Planet. Sci. Lett. 72 311. [7] Dickinson et al. LPSC 19th 189. *Acknowledgement*: Supported by the National Science Foundation and the Institute of Meteoritics.