Assessment of volatile depletion mechanisms for the Moon – pre-cursors, giant impact, core formation, post-impact loss.
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Introduction: The volatile element depletions in the Moon have been recognized for decades [1]. Multiple explanations have been debated, and arguments have become more quantitative, in large part due to new elemental partitioning and isotopic data [2-5]. Depletions in pre-cursor materials and due to post-accretion degassing have been evaluated using isotopic data. Partitioning of many volatile elements into metallic cores can now be evaluated for many volatile siderophile elements (VSE). Here is presented an evaluation of the role of core formation for 12 volatile siderophile elements for which partitioning data is now available. Examination of all 12 elements at once allows recognition of general trends, without undue focus on one element. Ga, Ge, Zn, Sn, As, Sb, Cd, Ag, Bi, P, In, Cu are all moderately to highly volatile, and will be discussed in their order of volatility as gauged by their 50% condensation temperature from [6].

Depletions: Mantle depletions are defined by correlations between the VSE and a refractory lithophile element (RLE) of comparable behavior during mantle melting (i.e., compatible or incompatible) in basalt and igneous rock suites from differentiated bodies. For Moon many mantle melt rocks are available from the Apollo collection or lunar meteorites, and can be used to reconstruct the mantle source concentrations if the behavior of the VSE and RLE is comparable and unfractionated during melting and differentiation [7]. Using this approach, and available data from the literature [8] the mantle concentrations of these 12 VSE were estimated.

Partitioning: Metal/silicate partitioning can be predicted for siderophile elements using the expression which has been derived elsewhere [e.g., 9]:

$$\ln D(i) = a\ln fO_2 + b/T + cP/T + \ln\gamma_i + g[nbo/t] + h \quad (1)$$

where γ_i is the activity of element i in Fe metallic liquid, nbo/t is the ratio of non-bridging oxygens to tetrahedrally coordinated cations and is a gauge of silicate melt compositional variation, and the coefficients a, b, c, g, and h are derived by multiple linear regression of various datasets. Regression coefficients and γ_i for the 12 VSE are available from recent experimental and partitioning studies [9-11]. These new constraints can be applied to lunar core formation.

Mantle concentrations: Knowing core size, bulk concentration, and degree of melting the mantle concentrations can be calculated according to:

$$C_{LS}^i = \frac{C_{bulk}^i}{x\left[p + (1-p)D_{SS/LS}^i\right] + (1-x)[D_{LM/LS}^i]} \quad (2)$$

where p is extent of melting, x is the mass fraction of mantle, and $D_{SS/LS}$ and $D_{LM/LS}$ are partition coefficients between solid silicate (SS), liquid silicate (LS) and liquid metal (LM). $D_{SS/LS}$ are available from the literature, and $D_{LM/LS}$ can be calculated according to eq. (1). p will be set to 1 for Moon and mantle fraction (x) is 0.985 [12]. The bulk composition of the Moon exhibits similarity to bulk silicate Earth, with volatile depletion of 4x defined by K, Na, Rb and Cs in BSE [13].

Calculated mantle concentrations for many of the VSE are comparable to estimates based on lunar samples. The most highly volatile elements – Cd, Bi, Sn, Zn, and In – are all depleted to lower values than expected from just BSE, core formation and a 4x depletion compared to BSE. This additional depletion might be due to a temperature dependent process in the lunar disk [14], or to post impact degassing from a magma ocean [15]. Comparison of isotopic variation in the moderately versus highly volatile elements may help to discriminate between these (or other) possibilities.

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Figure 1