

## PLANETARY SCIENCE

# Volatile element depletion of the Moon—The roles of precursors, post-impact disk dynamics, and core formation

K. Righter

The compositional and isotopic similarity of Earth's primitive upper mantle (PUM) and the Moon supports the derivation of the Moon from proto-Earth, but the Moon's inventory of volatile lithophile elements—Na, K, Rb, and Cs—is lower than Earth's PUM by factors of 4 to 5. The abundances of 14 other volatile elements exhibit siderophile behavior [volatile siderophile elements (VSEs); i.e., P, As, Cu, Ag, Sb, Ga, Ge, Bi, Pb, Zn, Sn, Cd, In, and Tl] that can be used to evaluate whether the Moon was derived from proto-Earth and if core formation or volatility controlled their depletion. At lunar core formation conditions, As, Sb, Ag, Ge, Bi, and Sn are siderophile, whereas P, Cu, Ga, Pb, Zn, Cd, In, and Tl are weakly siderophile or lithophile. VSEs may help to discriminate between physical and chemical processes that formed the Moon such as low- versus high-energy impacts and gas-melt interactions.

## INTRODUCTION

The similarity of Earth and the Moon isotopic composition (O, Ti, Ca, Fe, Mg, etc.), coupled with physical aspects such as angular momentum, lunar mass, and inclination, has led to various impact models for the origin of the Moon. The canonical late impactor (1) model showed that an impactor/proto-Earth mass ratio of 1:9 with a relatively low impact velocity would result in an Earth-Moon system that has many of the observed properties of our own. With relaxation of angular momentum constraints, more energetic collisions such as in highly spun up impactor and proto-Earth (2, 3) or 1:1 impactor/proto-Earth scenarios (3, 4) can also produce an Earth-Moon system as long as they are coupled with an angular momentum loss mechanism. Multiple smaller mass and energy impacts (5) can also produce an Earth-Moon system, with the overall energetics more similar to a canonical model. The latter three models are relatively new and grew out of the last decade of research exploring the details of angular momentum, lunar source material, and preimpact spin state constraints and have led to multiple working hypotheses for the lunar origin (1–5).

The volatile element depletions in the Moon have been recognized for decades (6, 7). Volatile elements can be depleted in the precursor (or building blocks) of the Moon, they can be depleted during the impact and post-impact processes that formed the Moon, and then, some can be partitioned into the Moon's metallic core. Although multiple explanations have been debated, and arguments have become more quantitative, the depletion of many volatile elements remains unexplained in detail. In this study, newly available core-mantle partitioning data for 14 volatile siderophile elements (VSEs) [e.g., (8–12) and references therein] are used to evaluate the roles of precursor volatility, disk dynamics, and core formation in establishing the lunar VSE depletion and to test the hypothesis that the Moon was derived from primitive upper mantle (PUM)-like material. Examination of all 14 elements (P, As, Cu, Ag, Sb, Ga, Ge, Bi, Pb, Zn, Sn, Cd, In, and Tl) at once allows recognition of general trends among the VSEs, without undue focus on one element. The VSE content of the lunar mantle will be updated using published data from lunar samples

(Apollo and Luna basalt and glass samples; see Materials and Methods). The three processes that determine whether PUM-like material could make the Moon (precursor volatile element depletion, protolunar disk dynamics, and lunar core formation) have been modeled to occur in three stages to separately assess their control on the VSE contents (see Materials and Methods).

## RESULTS

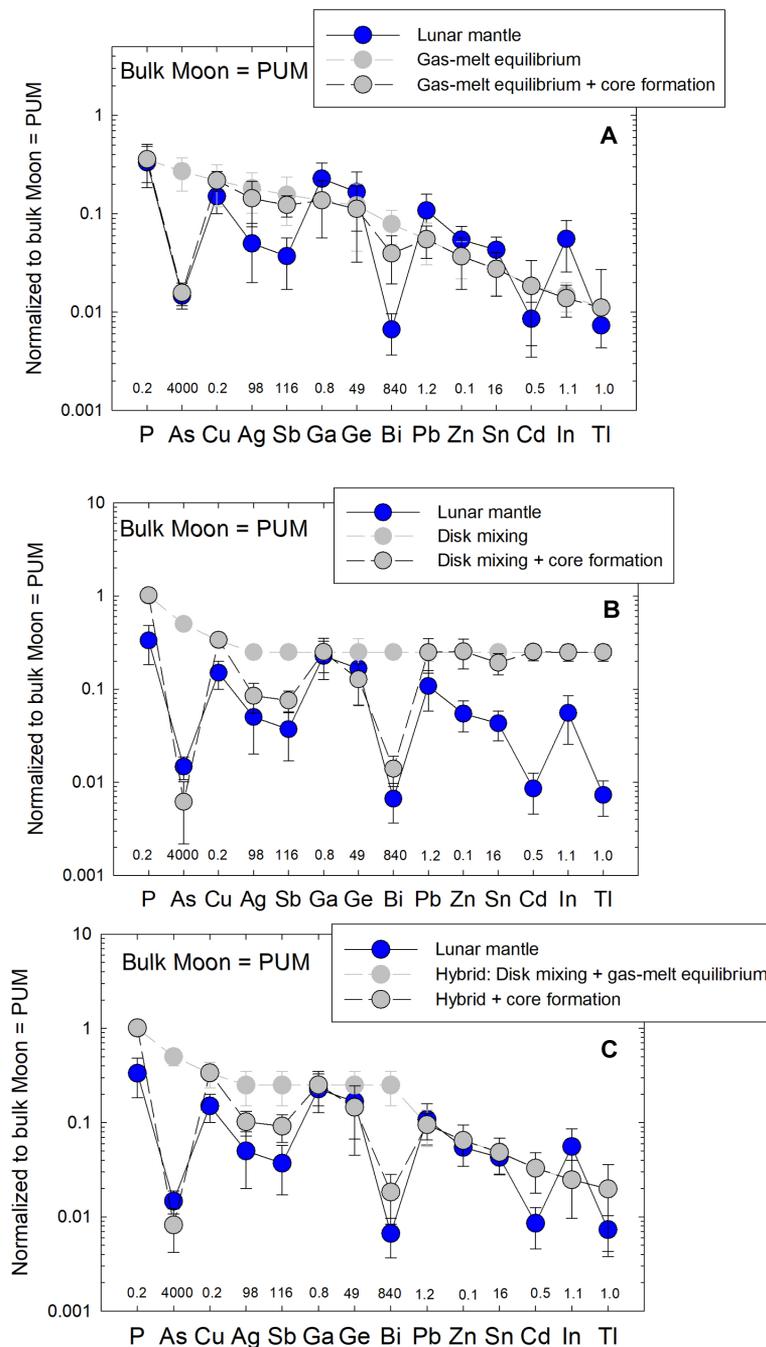
Using Eqs. 1 and 2 and a bulk silicate Earth composition (PUM) for the bulk Moon, we can examine several hypotheses for the origin of lunar volatiles. Discussion in the main text focuses on a PUM-like bulk Moon because this composition provides successful models for lunar mantle VSEs, as will be shown below. The two other Mars-sized impactor mantle bulk compositions do not provide successful models for the lunar mantle VSEs, and they are described in detail in section S4.

First, using a PUM composition, without an Earth-Moon volatility correction, unexpectedly results in lunar mantle VSE concentrations that are too high, indicating the need for depletion mechanisms in addition to stage 1. High-energy lunar formation models produce a gas-rich disk, indicating that the gas-melt fractionation may exert a strong control on volatile elements and can explain the 4× alkali element depletion of the Moon relative to Earth's mantle (3). Assuming that the least volatile element (P) and the most volatile element (Tl) can be explained by gas-melt fractionation with a gas fraction of 0.9 and by varying the  $D(\text{gas-melt})$  from 3 (P) to 100 (Tl) to fit these elements (see table S1) results in a good match to most of the VSEs, but concentrations are still too high for As, Ag, Sb, and Bi—a mismatch of >10 (stage 2; Fig. 1A). It is important to note that all four of these elements are moderately siderophile and thus have a substantial depletion due to core formation. When core formation is accounted for (stage 3), the fit to these four elements is improved, but Ag, Sb, and Bi remain mismatched by ~10 (Fig. 1A). Thus, a scenario of stages 1 to 3 with a gas-rich stage 2 explains many but not all of the VSEs.

Second, lower-energy lunar formation scenarios [such as canonical (1) or multiple impact (5) models] might involve mixing between volatile-depleted hot inner disk and cooler outer disk (volatile bearing) material, which (13) argues can also explain the factor of ~4 depletion of alkali elements in the Moon relative to Earth. If such mixing caused

Copyright © 2019  
The Authors, some  
rights reserved;  
exclusive licensee  
American Association  
for the Advancement  
of Science. No claim to  
original U.S. Government  
Works. Distributed  
under a Creative  
Commons Attribution  
NonCommercial  
License 4.0 (CC BY-NC).

Mailcode X12, NASA-JSC, 2101 NASA Parkway, Houston, TX 77058, USA.  
Email: kevin.righter-1@nasa.gov



**Fig. 1. Comparison of sample-based lunar mantle concentrations with those calculated in three stages.** Fourteen VSEs listed in the order of volatility as gauged by their 50% condensation temperature from (14). Blue symbols are lunar mantle estimates from correlations between the VSEs and a refractory lithophile element (RLE; see section S1). Three panels illustrate the three scenarios discussed in the text: gas-melt equilibrium followed by core formation, disk mixing followed by core formation, and a combination of gas-melt and disk mixing followed by core formation. All calculations assume a bulk Moon composition that is Earth's PUM. (A) The calculated lunar mantle if set by gas-melt equilibrium (light gray circles), followed by core formation (heavy gray circles). Gas-melt equilibrium is calculated using Eq. 2 with gas fraction = 0.9 and  $D$  (gas-melt) set for  $P = 3$  (least volatile) and  $TI = 100$  (most volatile) and is varied as a simple linear function for elements of intermediate volatility. For this scenario, Ag, Sb, and Bi are poor fits, while most other elements fit well. (B) The calculated mantle if set by mixing between hot inner disk and cooler volatile-bearing outer disk [as per (13); light gray circles], followed by core formation (heavy gray circles). Most of the moderately VSEs fit well in this scenario, but the higher-volatility Pb, Zn, Sn, Cd, In, and Tl are overabundant compared to the observed mantle concentrations. (C) The calculated lunar mantle for a hybrid model of combined disk mixing and gas-melt segregation (light gray circles), followed by core formation (heavy gray circles). The gas fraction in this model is 0.5, and the gas-melt partition coefficients are the same as for the first scenario (and summarized in table S1). This model fits all 14 elements well, including the Ag, Sb, and Bi contents that did not fit well in the first scenario. Values above the elements on the x axis are the metal-silicate partition coefficients calculated for lunar core formation conditions. Note that the high metal-silicate partition coefficient values for As, Ag, Sb, Ge, Bi, and Sn reflect more siderophile behavior, whereas P, Cu, Ga, Pb, Zn, Cd, In, and Tl are  $\leq 1$ , reflecting their more lithophile behavior.

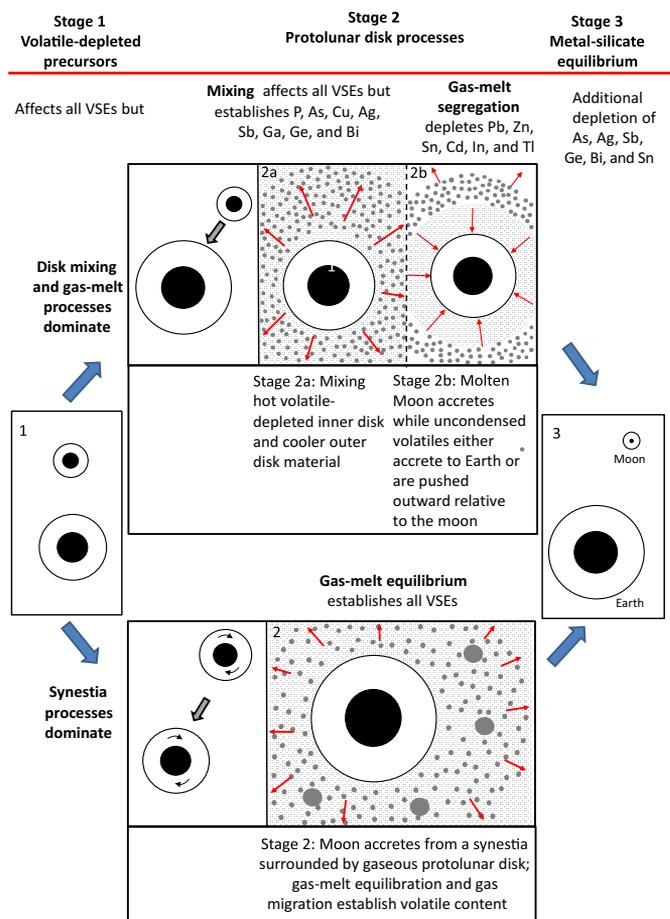
the overall bulk composition of the Moon to be depleted in volatile elements by  $\sim 4\times$ , then many VSEs can be satisfied (Fig. 1B). However, six critical VSEs (Pb, Zn, Cd, Sn, In, and Tl) would remain too high after mixing and require an additional depletion mechanism, since the stage 3 core formation would not significantly affect these six elements (Fig. 1B). Thus, although mixing within the disk can explain many elements, it does not explain the most highly depleted volatiles Pb, Zn, Cd, Sn, In, and Tl, and an additional loss mechanism would be required to explain their abundances.

A third scenario offers a hybrid solution that can explain most, if not all, VSEs. If mixing occurred in the early disk, then the moderately VSE contents of the bulk Moon may have been set by mixing between the hot inner and cool outer disks (Fig. 1C). The greater depletion of the more highly VSEs can be caused by temperature-dependent gas-melt interactions as the Moon accreted: The six highly VSEs may have remained in the gas phase as Moon accretion completed [with a gas fraction of 0.5 and with  $D(\text{gas-melt})$  being the same as for the first scenario; Fig. 1C]. The transition from these eight moderately VSEs to the six more highly VSEs at 50% condensation temperature ( $T_c \sim 725$  K) may correspond to an actual temperature near  $\sim 1700$  K (at 1 bar) (14, 15), perhaps reflecting the temperature for the top of the lunar photosphere [i.e.,  $\sim 2000$  K proposed by (16)]. The condensed lunar material would have to segregate from the gas-rich portion of the disk, which could migrate toward or away from Earth; if inward, then such late terrestrial accretion would have little effect on Earth's more highly VSE budget but would leave the Moon severely depleted in these six more highly VSEs. Last, further depletion of the siderophile As, Ag, Sb, and Bi due to core formation would leave the lunar mantle with a good fit to all 14 VSEs (Fig. 1C). Thus, volatile elements in the lunar mantle can be attributed to a combination of volatile-depleted precursors, mixing, and gas-melt equilibria in the protolunar disk, followed by lunar core formation.

## DISCUSSION

The hybrid scenario, involving both mixing and gas-melt equilibrium, would require a mechanism for gas-melt segregation, and currently, there are a number of viable possibilities. The combined modeling of Lindblad resonances in the inner disk and N-body simulations of the outer disk material has shown that the Moon accretes from a mixture of hot inner disk material and cooler outer disk material and that inner gas-rich disk material will ultimately fall back onto Earth (17). Alternatively, tidal interactions between the disk and the accreting Moon may cause migration of the forming body outward and away from the gas-rich portions of the disk (16, 17). On the other hand, magnetohydrodynamic modeling has suggested that turbulence-driven viscosity can lead to expansion of gas outward independent of the melt (18) and that post-impact disk volatilization can transport gas  $\sim 10$  Earth radii outward within several days of the impact (19). Turbulence at the gas-melt interface of a slightly higher pressure disk could move vapor outward as well (20, 21). Last, the vapor-rich environment of a synestia (3) coupled with disk dynamics offers potential for gas-melt segregation that could represent the more highly VSEs identified here. More work on gas-melt dynamics in the protolunar disk is obviously required.

Testing of the various Moon formation models for volatile contents has been incomplete, and the current work provides some guidance. Testing the canonical model has only quantitatively included Zn (13), but inclusion of additional elements, and measuring  $D(\text{VSE})$  gas-melt,



**Fig. 2. Schematic illustration of the stages proposed to explain the volatile element concentrations in the lunar mantle.** Stage 1 is the initial volatile-depleted precursor material. In this study, three different bulk Moon compositions are considered: terrestrial PUM, a Mars-sized impactor mantle that is less volatile depleted than PUM, and a Mars-sized impactor that is more volatile depleted than PUM. Stage 2 has two possible scenarios depicted in the top and bottom panels. **Top:** Stage 2a is caused by mixing of hot volatile-depleted inner disk material with cooler volatile-bearing outer disk material in the post-impact protolunar disk. Stage 2b is the segregation of melt and gas in the protolunar disk, which depleted the Moon of volatile elements with  $T_c$  (50%)  $< \sim 725$  K and may correspond to an actual temperature near  $\sim 1700$  K (at 1 bar) (14, 15), perhaps reflecting the temperature for the top of the lunar photosphere [i.e.,  $\sim 2000$  K proposed by (16)]. The pattern of volatile element depletion may thus reflect the thermal structure of the protolunar disk or a quasi-steady-state temperature at the top of the photosphere (21). Remaining gas might move inward or outward depending on the driving physical mechanism. **Bottom:** Stage 2 is a simple gas-melt equilibrium such as may exist in a terrestrial synestia (3). Last, stage 3 is the formation of the lunar core that further depleted the most siderophile elements As, Ag, Sb, Ge, Bi, and Sn. A multistage model (disk mixing and gas-melt equilibrium) can potentially provide a quantitative explanation for these 14 VSEs and lithophile volatile elements Li, Na, K, Rb, and Cs but needs to be tested for specific lunar formation models (see detailed discussion in the main text).

should reveal whether gas-melt dynamics in the lunar disk established the VSE pattern for the bulk silicate Moon. We show above that a three-stage process could potentially explain the lunar VSEs. More energetic lunar formation models include a collision between a highly spun proto-Earth and impactor that forms a high-temperature protolunar disk (2, 3) or a direct collision that produces a terrestrial synestia out of which the Moon accretes (3, 4). The moderately volatile element

depletions may reflect equilibration between disk melt and vapor during cooling at pressures between 10 and 50 bar as was shown for Cu and Zn (3). Calculations for Ge, however, result in values lower than lunar mantle estimates and do not account for the siderophile nature of Ge ( $D_{\text{metal-silicate}} = 50$ ) that will result in a more severe depletion than previously calculated (3). The ability of the synestia model to account for both the moderately and highly VSEs will require examination of more elements. For example, Lock *et al.* (3) argue that the behavior of some VSEs is pressure dependent but these authors only model Cu, Zn, and Ge, which have similar pressure effects. Including more elements will provide more leverage of the pressure dependence: Increased pressure causes Ga and Zn to switch their degree of volatility, while Pb becomes more volatile (22). In addition, the relative volatility of some of the VSEs changes if nonideality is considered (22, 23): In, Sb, As, and Bi all become less volatile (and Zn and Ge become more volatile).

The close similarity of lunar mantle VSE estimates (from samples) to those calculated assuming that the bulk Moon is similar to the terrestrial PUM is supportive of the idea that the Moon was derived from proto-Earth. Our new calculations and assessments using this large group of elements illustrate the degree of volatile depletion across a wide temperature range for the Moon and establish an important baseline for interpreting and evaluating lunar origin models in the future. The effect of core formation on the moderately siderophile VSEs (As, Sb, Ag, Ge, Bi, and Sn) must be included in any modeling efforts. The origin of volatiles might also be tested by combining the bulk VSE contents with Ga, Zn, Cl, and K isotopic variation in lunar and terrestrial samples (24–27). Future modeling (i) that quantifies precursor materials, disk-melt interactions, and core-mantle partitioning, (ii) that includes pressure and nonideality constraints on gas-melt equilibria for more elements, and (iii) that has the strong effects of core formation is likely to provide an important test of lunar formation models for volatile elements. Specifically, the VSEs may help to understand the chemical (evaporation, condensation) and physical (disk dynamics, core formation) processes, and discriminate between lower-energy [canonical (1) or multiple impact (5)] and higher-energy [synestia (3, 4) and sub-Earth (2, 3)] models for the origin of the Moon.

## MATERIALS AND METHODS

### Lunar mantle concentrations of VSEs—Constraints from samples

Mantle concentrations were defined by correlations between the VSEs and a refractory lithophile element (RLE) of comparable behavior during mantle melting (i.e., compatible or incompatible) in basalt and volcanic glass suites from differentiated bodies (28). Many lunar mantle melts (basalts and volcanic glasses) from the Apollo and lunar meteorite collections were analyzed and were used to reconstruct the mantle source concentrations of the VSEs using a known and comparable behavior of the VSEs and RLEs, which are unfractionated during melting and differentiation [e.g., (29–34)] (see section S1 and figs. S1 and S2 for summary and data file S1 for full sample analyses and details).

### Modeling the VSE content of the lunar mantle

In modeling the VSE content of the lunar mantle, several stages, which reflect known processes that contributed to the formation of the Moon, are considered: Stage 1 represents the degree to which the bulk Moon composition was volatile depleted; stage 2 represents the process(es)

after the Moon-forming impact(s) that controlled the accretion of the Moon from a gas-melt disk; and stage 3 represents the syn- or post-accretion segregation of a metallic core and its equilibration with the mantle. These processes were likely separated in time and represent distinct processes and thus are referred to here as stages (Fig. 2).

### Stage 1: Volatile-depleted building blocks

Most inner solar system bodies have a recognized volatile element depletion relative to chondritic proportions that originated with the building blocks or precursors, and Earth is no exception. Three different lunar bulk compositions that represent possible scenarios for Moon formation were considered: (i) The bulk Moon is from the terrestrial PUM (35–38), as suggested in some formation models for the Moon; (ii) the bulk Moon is from a Mars-sized (but initially more volatile-rich than PUM) impactor mantle for which we will use Mars as a proxy, and the mantle and bulk composition of Mars are relatively well known from meteorite studies and geochemical constraints (39, 40); and (iii) the bulk Moon is from a Mars-sized (but initially more volatile-depleted than PUM) impactor mantle, similar in overall bulk composition to Earth. Bulk compositions are described in more detail and discussed in section S2.

### Stage 2: Protolunar disk dynamics

Most lunar formation models predict that, after an impact, the Moon will accrete from a disk of material that surrounds proto-Earth, as either a gas-melt disk (2) or a synestia (3). This material is likely to be initially hot and largely vapor and then, upon cooling, a mixture of melt and gas, so the volatile content of the Moon may depend on either mixing within the disk (13) or partitioning between melt and gas (3) and on the possibility of subsequent gas-melt segregation in the disk. Elemental fractionation during condensation of the impact-generated vapor is not expected (3), but the remaining gas would later be incorporated into the protolunar disk. Is there a gas-melt segregation mechanism that is consistent with the early lunar disk thermal structure that can also explain the pattern of volatile element depletion in the Moon?

Mixing between the inner volatile-depleted and outer volatile-bearing disks was proposed (13) as a way to explain the volatile depletions in the Moon and is modeled here by modifying the bulk composition of the Moon to match the volatile lithophile element (Li, Na, K, Rb, and Cs) concentrations in the lunar mantle, assuming that they are due to mixing. Depletion of the volatile lithophile elements in the three bulk compositions was guided by comparisons with Earth's PUM, where Moon/Earth ratios are known to be  $\sim 1$  for Li and  $\sim 0.25$  for Na, K, Rb, and Cs, and corresponding adjustments to VSE contents must be made (see section S3 and fig. S3).

Disk modeling identified segregation mechanisms for melt and gas in the protolunar disk, but there is currently little agreement and a need for additional work. The details and timing of the early stages of lunar history are uncertain, but there are several physical settings and models that can segregate melt and gas, moving gas either inward or outward relative to the melt, including disk resonances, disk-Moon tidal interactions, or turbulence at the gas-melt interface (see discussion below). Gas-melt partitioning was captured with a simple term in Eq. 2 that quantifies the partitioning of an element between gas and silicate melt, and the gas fraction of the system, understanding that the specific mechanism has not yet been identified, as discussed below. This term is meant to be illustrative of possible gas-melt equilibrium and not demonstrative but is motivated by expected behavior for these elements.

### Stage 3: Core formation

Previous work showed that a wide range of mantle siderophile element concentrations (e.g., Ni, Co, Mo, W, V, and Cr) can be explained by the equilibration of a small metallic core with the mantle, at ~4.5 GPa, ~2273 K, and oxygen fugacity near IW-1, where IW-1 refers to the oxygen fugacity 1 logfO<sub>2</sub> unit below the iron-wüstite buffer (41–43). Metal-silicate partitioning was predicted for 13 of the VSEs using an expression derived elsewhere [e.g., (44)]

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

where  $\gamma_i$  is the activity of element  $i$  in Fe metallic liquid (table S1),  $nbo/t$  is the ratio of nonbridging oxygens to tetrahedrally coordinated cations and is a gauge of silicate melt compositional variation [a value of 2.8 for the bulk silicate Moon (41)], and the coefficients  $a$ ,  $b$ ,  $c$ ,  $g$ , and  $h$  are derived by multiple linear regression of various datasets. Regression coefficients and  $\gamma_i$  for the VSEs are available from recent experimental and partitioning studies (see table S1 for more information about the partition coefficients). Tl partitioning studies among metal, sulfide, and silicate melt reveal that Tl is compatible in sulfur-rich or sulfide liquids but weakly siderophile to lithophile at the S-poor conditions of lunar core formation, so we have adopted  $D(Tl)_{\text{metal-silicate}} = 1$  for the Moon (Supplementary Materials and table S1). These new constraints were applied to lunar core formation, with the additional assumption that equilibration between the core metal and the lunar mantle is complete, which is the expected outcome in lunar-sized bodies experiencing impacts (45).

### Calculation of lunar mantle VSEs resulting from three processes

Combining these three stages can be done using a simple approach tracking gas, melt, and metallic liquid phases that are relevant to the early Moon environment. One can calculate the concentrations of VSEs resulting in the lunar mantle,  $C_{\text{sil}}^i$ , according to

$$\begin{aligned} C_{\text{bulk}}^i &= x C_{\text{sil}}^i + (0.985 - x) C_{\text{gas}}^i + 0.015 C_{\text{met}}^i \\ C_{\text{bulk}}^i / C_{\text{sil}}^i &= x + (0.985 - x) C_{\text{gas}}^i / C_{\text{sil}}^i + 0.015 C_{\text{met}}^i / C_{\text{sil}}^i \\ C_{\text{sil}}^i &= C_{\text{bulk}}^i / \left[ x + (0.985 - x) D_{\text{gas/sil}}^i + 0.015 D_{\text{met/sil}}^i \right] \quad (2) \end{aligned}$$

where  $x$  is the mass fraction of the Moon that was supplied from a silicate melt phase (so that, in the limiting case where all of the Moon's silicate was derived from the melt,  $x = 0.985$  for a metal core fraction of 0.015),  $C_{\text{bulk}}^i$  is the bulk composition of the VSEs in the Moon (see the "Stage 1: Volatile-depleted building blocks" section), the core fraction is 0.015 from GRAIL (Gravity Recovery and Interior Laboratory) constraints (46), and  $D_{\text{met/sil}}^i$  is calculated according to Eq. 1 (see the "Stage 3: Core formation" section).

### SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/5/1/eaau7658/DC1>

Section S1. Lunar mantle concentrations of the VSEs

Section S2. Bulk Moon compositions

Section S3. Disk mixing assumptions

Section S4. Alternative models with impactor bulk compositions

Fig. S1. Hypothetical behavior of a siderophile-RLE pair during mantle melting and subsequent processes (trapped metal, residual sulfide, and later degassing).

Fig. S2A. Correlations of 12 VSEs with a refractory lithophile element of similar degree of incompatibility.

Fig. 2B. Pb-Ce correlation.

Fig. S3. Volatile lithophile element corrections for bulk Moon compositions.

Fig. S4. Model calculations for bulk Moon = primitive martian mantle.

Fig. S5. Model calculations for bulk Moon = Mars-sized impactor mantle.

Table S1. Summary of bulk and mantle compositions, volatility corrections, activity coefficients, and core-mantle regression coefficients.

Data file S1. Lunar data (Excel).

References (47–102)

### REFERENCES AND NOTES

- R. M. Canup, Lunar-forming collisions with pre-impact rotation. *Icarus* **196**, 518–538 (2008).
- R. M. Canup, Forming a Moon with an Earth-like composition via a giant impact. *Science* **338**, 1052–1055 (2012).
- S. J. Lock, S. T. Stewart, M. I. Petaev, Z. Leinhardt, M. T. Mace, S. B. Jacobsen, M. Cuk, The origin of the Moon within a terrestrial synestia. *J. Geophys. Res. Planets* **123**, 910–951 (2018).
- M. Cuk, S. T. Stewart, Making the Moon from a fast-spinning Earth: A giant impact followed by resonant despinning. *Science* **338**, 1047–1052 (2012).
- R. Rufu, O. Aharonson, H. B. Perets, A multiple-impact origin for the Moon. *Nat. Geosci.* **10**, 89–94 (2017).
- A. E. Ringwood, S. E. Kesson, Composition and origin of the Moon. *Proc. Lun. Planet. Sci. Conf.* **8**, 371–398 (1977).
- A. E. Ringwood, Volatile and siderophile element geochemistry of the Moon: A reappraisal. *Earth Planet. Sci. Lett.* **111**, 537–555 (1992).
- U. Mann, D. J. Frost, D. C. Rubie, Evidence for high-pressure core-mantle differentiation from the metal-silicate partitioning of lithophile and weakly-siderophile elements. *Geochim. Cosmochim. Acta* **73**, 7360–7386 (2009).
- E. S. Kiseeva, B. J. Wood, A simple model for chalcophile element partitioning between sulphide and silicate liquids with geochemical applications. *Earth Planet. Sci. Lett.* **383**, 68–81 (2013).
- K. Righter, K. Pando, N. Marin, D. K. Ross, M. Righter, L. R. Danielson, T. J. Lapen, C. T. Lee, Volatile element signatures in the mantles of Earth, Moon, and Mars: Core formation fingerprints from Bi, Cd, In, and Sn. *Meteorit. Planet. Sci.* **53**, 284–305 (2018).
- K. Righter, K. Nickodem, K. Pando, L. Danielson, A. Boujibar, M. Righter, T. J. Lapen, Distribution of Sb, As, Ge, and In between metal and silicate during accretion and core formation in the Earth. *Geochim. Cosmochim. Acta* **198**, 1–16 (2017).
- J. Siebert, A. Corgne, F. J. Ryerson, Systematics of metal-silicate partitioning for many siderophile elements applied to Earth's core formation. *Geochim. Cosmochim. Acta* **75**, 1451–1489 (2011).
- R. M. Canup, C. Visscher, J. Salmon, B. Fegley Jr., Lunar volatile depletion due to incomplete accretion within an impact-generated disk. *Nat. Geosci.* **8**, 918–922 (2015).
- K. Lodders, Solar system abundances and condensation temperatures of the elements. *Astrophys. J.* **591**, 1220–1240 (2003).
- P. Sossi, S. Klemme, H. O'Neill, J. Berndt, F. Moynier, Experimental constraints on the evaporation of moderately volatile elements during planetary formation. *Goldschmidt Abstract 2017*, abstract no. 3729 (2017).
- W. R. Ward, On the evolution of the protolunar disk. *Phil. Trans. R. Soc. A* **372**, 20130250 (2014).
- J. Salmon, R. M. Canup, Lunar accretion from a Roche-interior fluid disk. *Astrophys. J.* **760**, 83–95 (2012).
- A. Carballido, S. J. Desch, G. J. Taylor, Magneto-rotational instability in the protolunar disk. *Icarus* **268**, 89–101 (2016).
- C. F. Gammie, W.-T. Liao, P. M. Ricker, A hot big bang theory: Magnetic fields and the early evolution of the protolunar disk. *Astrophys. J.* **828**, 58–68 (2016).
- S. Charnoz, C. Michaut, Evolution of the protolunar disk: Dynamics, cooling timescale and implantation of volatiles onto the Earth. *Icarus* **260**, 440–463 (2015).
- W. R. Ward, On the vertical structure of the protolunar disk. *Astrophys. J.* **744**, 140–152 (2012).
- L. Schaefer, B. Fegley Jr., Volatile element chemistry during metamorphism of ordinary chondritic material and some of its implications for the composition of asteroids. *Icarus* **205**, 483–496 (2010).
- C. A. Norris, B. J. Wood, Earth's volatile contents established by melting and vaporization. *Nature* **549**, 507–510 (2017).
- K. Wang, S. B. Jacobsen, Potassium isotopic evidence for a high-energy giant impact origin of the Moon. *Nature* **538**, 487–490 (2016).
- C. Kato, F. Moynier, Gallium isotopic evidence for extensive volatile loss from the Moon during its formation. *Sci. Adv.* **3**, e1700571 (2017).

26. R. C. Paniello, J. M. D. Day, F. Moynier, Zinc isotopic evidence for the origin of the Moon. *Nature* **490**, 376–379 (2012).
27. Z. D. Sharp, C. K. Shearer, K. D. McKeegan, J. D. Barnes, Y. Q. Wang, The chlorine isotope composition of the Moon and implications for an anhydrous mantle. *Science* **329**, 1050–1053 (2010).
28. M. J. Drake, Trace elements as quantitative probes of differentiation processes in planetary interiors. *Rev. Geophys.* **18**, 11–25 (1980).
29. H. Wänke, H. Baddenhausen, A. Balacescu, F. Teschke, B. Spettel, G. Dreibus, H. Palme, M. Quijano-Rico, H. Kruse, F. Wlotzka, F. Begemann, Multi-element analyses of lunar samples and some implications of the results. *Proc. Third Lunar Planet. Sci. Conf.* **2**, 1251–1269 (1972).
30. H. Wänke, H. Palme, H. Baddenhausen, G. Dreibus, E. Jagoutz, H. Kruse, B. Spettel, F. Teschke, R. Thacker, Chemistry of Apollo 16 and 17 samples-Bulk composition, late stage accumulation and early differentiation of the moon. *Proc. Fifth Lunar Planet. Sci. Conf.* **2**, 1307–1335 (1974).
31. H. Wänke, H. Palme, H. Baddenhausen, G. Dreibus, E. Jagoutz, H. Kruse, C. Palme, B. Spettel, F. Teschke, R. Thacker, New data on the chemistry of lunar samples-Primary matter in the lunar highlands and the bulk composition of the moon. *Proc. Sixth Lunar Planet. Sci. Conf.* **2**, 1313–1340 (1975).
32. H. Palme, H. Baddenhausen, K. Blum, M. Cendales, G. Dreibus, H. Hofmeister, H. Kruse, C. Palme, B. Spettel, E. Vilcek, H. Wänke, G. Kurat, New data on lunar samples and achondrites and a comparison of the least fractionated samples from the Earth, the moon and the eucrite parent body. *Proc. Ninth Lunar Planet. Sci. Conf.* **1**, 25–57 (1978).
33. R. Wolf, A. Woodrow, E. Anders, Lunar basalts and pristine highland rocks—Comparison of siderophile and volatile elements. *Proc. 10th Lunar Planet. Sci. Conf.* **2**, 2107–2130 (1979).
34. C. K. Meyer Jr., Lunar sample compendium; <https://curator.jsc.nasa.gov/lunar/lsc/index.cfm>.
35. N. Dauphas, C. Burkhardt, P. H. Warren, T. Fang-Zhen, Geochemical arguments for an Earth-like Moon-forming impactor. *Philos. Trans. A Math. Phys. Eng. Sci.* **372**, 20130244 (2014).
36. P. H. Warren, The magma ocean concept and lunar evolution. *Annu. Rev. Earth Planet. Sci.* **13**, 201–240 (1985).
37. H. Palme, H. St. C. O'Neill, Cosmochemical estimates of mantle composition, in *Treatise on Geochemistry*, A. M. Davis, Ed. (Elsevier, ed. 2, 2014), pp. 1–39.
38. J. H. Jones, H. Palme, Geochemical constraints on the origin of the Earth and Moon, in *Origin of the Earth and Moon*, R. Canup, K. Righter, Eds. (University of Arizona Press, 2000) pp. 197–216.
39. G. J. Taylor, The bulk composition of Mars. *Chem. Erde-Geochem.* **73**, 401–420 (2013).
40. S. Yang, M. Humayun, K. Righter, G. Jefferson, D. Fields, A. J. Irving, Siderophile and chalcophile element abundances in shergottites: Implications for Martian core formation. *Meteorit. Planet. Sci.* **50**, 691–714 (2015).
41. K. Righter, Does the Moon have a metallic core?: Constraints from giant impact modeling and siderophile elements. *Icarus* **158**, 1–13 (2002).
42. M. Sharp, K. Righter, R. J. Walker, Estimation of trace element concentrations in the lunar magma ocean using mineral-and metal-silicate melt partition coefficients. *Meteorit. Planet. Sci.* **50**, 733–758 (2015).
43. E. S. Steenstra, N. Rai, J. S. Knibbe, Y. H. Lin, W. van Westrenen, New geochemical models of core formation in the Moon from metal-silicate partitioning of 15 siderophile elements. *Earth Planet. Sci. Lett.* **441**, 1–9 (2016).
44. K. Righter, L. R. Danielson, K. M. Pando, G. A. Hofner, S. R. Sutton, M. Newville, C.-T. Lee, Valence and metal/silicate partitioning of Mo: Implications for conditions of Earth accretion and core formation. *Earth Planet. Sci. Lett.* **437**, 89–100 (2016).
45. J. D. Kendall, H. J. Melosh, Differentiated planetesimal impacts into a terrestrial magma ocean: Fate of the iron core. *Earth Planet. Sci. Lett.* **448**, 24–33 (2016).
46. J. G. Williams, A. S. Konopliv, D. H. Boggs, R. S. Park, D.-N. Yuan, F. G. Lemoine, S. Goossens, E. Mazarico, F. Nimmo, R. C. Weber, S. W. Asmar, H. Jay Melosh, G. A. Neumann, R. J. Phillips, D. E. Smith, S. C. Solomon, M. M. Watkins, M. A. Wieczorek, J. C. Andrews-Hanna, J. W. Head, W. S. Kiefer, I. Matsuyama, P. J. McGovern, G. Jeffrey Taylor, M. T. Zuber, Lunar interior properties from the GRAIL mission. *J. Geophys. Res.* **119**, 1546–1578 (2014).
47. H. Wänke, G. Dreibus, Geochemical evidence for the formation of the Moon by impact-induced fission of the proto-Earth, in *Origin of the Moon*, Proceedings of the Conference, Kona, HI, October 13 to 16, W. K. Hartmann, R. J. Phillips, G. J. Taylor, Eds. (1986), pp. 649–671.
48. K. Righter, J. T. Chesley, C. M. Caiazza, E. K. Gibson Jr., J. Ruiz, Re and Os concentrations in arc basalts: The roles of volatility and source region fO<sub>2</sub> variations. *Geochim. Cosmochim. Acta* **72**, 926–947 (2008).
49. P. A. Danckwerth, P. C. Hess, M. J. Rutherford, The solubility of sulfur in high-TiO<sub>2</sub> mare basalts. *Proc. 10th Lunar Planet. Sci. Conf.* **1**, pp. 517–530 (1979).
50. E. K. Gibson, R. Brett Jr., F. Andrawes, Sulfur in lunar mare basalts as a function of bulk composition. *Proc. Eighth Lunar Planet. Sci. Conf.* **2**, pp. 1417–1428 (1977).
51. K. Rubin, Degassing of metals and metalloids from erupting seamount and mid-ocean ridge volcanoes: Observations and predictions. *Geochim. Cosmochim. Acta* **61**, 3525–3542 (1997).
52. A. E. Saal, E. H. Hauri, M. L. Cascio, J. A. Van Orman, M. C. Rutherford, R. F. Cooper, Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. *Nature* **454**, 192–195 (2008).
53. D. S. McKay, S. J. Wentworth, Morphology and composition of condensates on Apollo 17 orange and black glass. Lunar Science Inst., Workshop on Geology of the Apollo 17 Landing Site (1992), pp. 31–36.
54. C. Meyer Jr., D. S. McKay, D. H. Anderson, P. Butler Jr., The source of sublimates on the Apollo 15 green and Apollo 17 orange glass samples. *Proc. Sixth Lunar Planet. Sci. Conf.* **2**, pp. 31–36 (1975).
55. G. F. Herzog, F. Moynier, F. Albarède, A. A. Berezhnoy, Isotopic and elemental abundances of copper and zinc in lunar samples, Zagami, Pele's hairs, and a terrestrial basalt. *Geochim. Cosmochim. Acta* **73**, 5884–5904 (2009).
56. C. J. Renggli, P. L. King, R. W. Henley, M. D. Norman, Volcanic gas composition, metal dispersion and deposition during explosive volcanic eruptions on the Moon. *Geochim. Cosmochim. Acta* **206**, 296–311 (2017).
57. C. K. Shearer, J. J. Papike, S. B. Simon, N. Shimizu, H. Yurimoto, S. Sueno, Ion microprobe studies of trace elements in Apollo 14 volcanic glass beads: Comparisons to Apollo 14 mare basalts and petrogenesis of picritic magmas. *Geochim. Cosmochim. Acta* **54**, 851–867 (1990).
58. T. Dickinson, G. J. Taylor, K. Keil, R. W. Bild, Germanium abundances in lunar basalts—Evidence of mantle metasomatism? *Proc. 19th Lunar Planet. Sci. Conf.* **19**, pp. 189–198 (1989).
59. H. E. Newsom, Constraints on the origin of the Moon from the abundance of molybdenum and other siderophile elements, in *Origin of the Moon*, Proceedings of the Conference, Kona, HI, October 13 to 16, W. K. Hartmann, R. J. Phillips, G. J. Taylor, Eds. (1986), pp. 203–229.
60. Basaltic Volcanism Study Project, *Basaltic Volcanism on the Terrestrial Planets* (Pergamon Press, 1981).
61. A. O. Brunfelt, K. S. Heier, E. Steinnes, Determination of 40 elements in Apollo 12 materials by neutron activation analysis. *Proc. Second Lunar Planet. Sci. Conf.* **2**, pp. 1281–1290 (1971).
62. H. Wänke, R. Rieder, H. Baddenhausen, B. Spettel, F. Teschke, M. Quijano-Rico, A. Balacescu, Major and trace elements in lunar material. *Proc. First Lunar Planet. Sci. Conf.* **2**, pp. 1719–1736 (1970).
63. H. Wänke, F. Wlotzka, H. Baddenhausen, A. Balacescu, B. Spettel, F. Teschke, E. Jagoutz, H. Kruse, M. Quijano-Rico, R. Rieder, Apollo 12 samples: Chemical composition and its relation to sample locations and exposure ages, the two-component origin of the various soil samples and studies on lunar metallic particles. *Proc. Second Lunar Planet. Sci. Conf.* **2**, pp. 1187–1199 (1971).
64. H. Wänke, H. Baddenhausen, G. Dreibus, E. Jagoutz, H. Kruse, H. Palme, B. Spettel, F. Teschke, Multi-element analyses of Apollo 15, 16 and 17 samples and the bulk composition of the Moon. *Proc. Fourth Lunar Planet. Sci. Conf.* **2**, 1461–1481 (1973).
65. H. Wänke, H. Baddenhausen, K. Blum, M. Cendales, G. Dreibus, H. Hofmeister, H. Kruse, E. Jagoutz, C. Palme, B. Spettel, R. Thacker, On the chemistry of lunar samples and achondrites-Primary matter in the lunar highlands: A re-evaluation. *Proc. Eighth Lunar Planet. Sci. Conf.* **2**, 2191–2213 (1977).
66. G. A. Snyder, C. R. Neal, L. A. Taylor, A. N. Halliday, Anatexis of lunar cumulate mantle in time and space: Clues from trace-element, strontium, and neodymium isotopic chemistry of parental Apollo 12 basalts. *Geochim. Cosmochim. Acta* **61**, 2731–2747 (1997).
67. G. Ryder, B. C. Schuraytz, Chemical variation of the large Apollo 15 olivine-normative mare basalt rock samples. *J. Geophys. Res. Planets* **106**, 1435–1451 (2001).
68. S. R. Taylor, R. Rudowski, P. Muir, A. Graham, M. Kaye, Trace element chemistry of lunar samples from the Ocean of Storms. *Proc. Second Lunar Planet. Sci. Conf.* **2**, 1083–1099 (1971).
69. P. H. Warren, D. N. Shirley, G. W. Kallemeyn, A potpourri of pristine Moon rocks, including a VHk mare basalt and a unique, augite-rich Apollo 17 anorthosite. *J. Geophys. Res. Solid Earth* **91**, 319–330 (1986).
70. M. D. Norman, K. J. D. Adena, A. G. Christy, Provenance and Pb isotopic ages of lunar volcanic and impact glasses from the Apollo 17 landing site. *Aust. J. Earth Sci.* **59**, 291–306 (2012).
71. F. Albarède, E. Albalat, C.-T. A. Lee, An intrinsic volatility scale relevant to the Earth and Moon and the status of water in the Moon. *Meteorit. Planet. Sci.* **50**, 568–577 (2015).
72. E. H. Hauri, A. E. Saal, M. J. Rutherford, J. A. Van Orman, Water in the Moon's interior: Truth and consequences. *Earth Planet. Sci. Lett.* **409**, 252–264 (2015).
73. J. W. Morgan, G. A. Wandless, R. K. Petrie, A. J. Irving, Composition of the earth's upper mantle-II: Volatile trace elements in ultramafic xenoliths. *Proc. 11th Lunar Planet. Sci. Conf.* **1**, 213–233 (1980).

74. J. Hertogen, M.-J. Janssens, H. Palme, Trace elements in ocean ridge basalt glasses: implications for fractionations during mantle evolution and petrogenesis. *Geochim. Cosmochim. Acta* **44**, 2125–2143 (1980).
75. K. P. Jochum, A. W. Hofmann, H. M. Seufert, Tin in mantle-derived rocks: Constraints on Earth evolution. *Geochim. Cosmochim. Acta* **57**, 3585–3595 (1993).
76. W. Yi, A. N. Halliday, D.-C. Lee, J. N. Christensen, Indium and tin in basalts, sulfides, and the mantle. *Geochim. Cosmochim. Acta* **59**, 5081–5090 (1995).
77. W. Yi, A. N. Halliday, J. C. Alt, D.-C. Lee, M. O. Garcia, Y. Su, Cadmium, indium, tin, tellurium, and sulfur in oceanic basalts: Implications for chalcophile element fractionation in the Earth. *J. Geophys. Res. Solid Earth* **105**, 18927–18948 (2000).
78. M. D. Norman, M. O. Garcia, V. C. Bennett, Rhenium and chalcophile elements in basaltic glasses from Ko'olau and Moloka'i volcanoes: Magmatic outgassing and composition of the Hawaiian plume. *Geochim. Cosmochim. Acta* **68**, 3761–3777 (2004).
79. G. Witt-Eickschen, H. Palme, H. S. C. O'Neill, C. M. Allen, The geochemistry of the volatile trace elements As, Cd, Ga, In and Sn in the Earth's mantle: New evidence from in situ analyses of mantle xenoliths. *Geochim. Cosmochim. Acta* **73**, 1755–1778 (2009).
80. F. E. Jenner, R. J. Arculus, J. A. Mavrogenes, N. J. Dyrwi, O. Nebel, E. H. Hauri, Chalcophile element systematics in volcanic glasses from the northwestern Lau Basin. *Geochim. Geophys. Geosyst.* **13**, 1–25 (2010).
81. K. P. Jochum, U. Weis, B. Schwager, B. Stoll, S. A. Wilson, G. H. Haug, M. O. Andreae, J. Enzweiler, Reference values following ISO guidelines for frequently requested rock reference materials. *Geostand. Geoanal. Res.* **40**, 333–350 (2016).
82. A. Johnson, D. Canil, The degassing behavior of Au, Ti, As, Pb, Re, Cd and Bi from silicate liquids: Experiments and applications. *Geochim. Cosmochim. Acta* **75**, 1773–1784 (2011).
83. F. Moynier, F. Albarède, G. F. Herzog, Isotopic composition of zinc, copper, and iron in lunar samples. *Geochim. Cosmochim. Acta* **70**, 6103–6117 (2006).
84. M. Humayun, N. DiFrancesco, G. Ustunisi, Experimental confirmation of the volatility of germanium in martian basalts, in *79th Annual Meeting of the Meteoritical Society*, LPI Contrib. No. 1921, #6491 (2016).
85. G. Ustunisi, N. DiFrancesco, S. Yang, M. Humayun, A. Rogaski, Role of Cl and S on the volatility of Ge, Zn, and Li in martian basaltic magmas: Implications for volatile contribution to martian surface lithologies, in *Conference of the 49th Lunar and Planetary Science Conference* (2018), 2659 p.
86. G. J. Taylor, M. A. Wieczorek, Lunar bulk chemical composition: A post-Gravity Recovery and Interior Laboratory reassessment. *Phil. Trans. A Math. Phys. Eng. Sci.* **372**, 20130242 (2014).
87. D. L. Turcotte, G. Schubert, *Geodynamics: Applications of Continuum Physics to Geological Problems* (John Wiley and Sons, 1982).
88. H. E. Newsom, Composition of the solar system, planets, meteorites, and major terrestrial reservoirs. *Glob. Earth Phys.* **1**, 159–189 (1995).
89. C. R. Neal, Interior of the Moon: The presence of garnet in the primitive deep lunar mantle. *J. Geophys. Res. Planets* **106**, 27865–27885 (2001).
90. M. Tatsumoto, R. J. Knight, B. R. Doe, U-Th-Pb systematics of Apollo 12 lunar samples. *Proc. Second Lunar Planet. Sci. Conf.* **2**, 1521–1546 (1971).
91. M. Tatsumoto, W. R. Premo, D. M. Unruh, Origin of lead from Green Glass of Apollo 15426: A search for primitive lunar lead. *J. Geophys. Res. Solid Earth* **92**, E361–E371 (1987).
92. P. D. Nunes, M. Tatsumoto, D. M. Unruh, U-Th-Pb systematics of some Apollo 17 lunar samples and implications for a lunar basin excavation chronology. *Proc. Fifth Lunar Planet. Sci. Conf.* **2**, 1487–1514 (1974).
93. P. D. Nunes, M. Tatsumoto, U-Th-Pb systematics of selected samples from Apollo 17, Boulder 1, Station 2. *The Moon* **14**, 463–471 (1975).
94. G. R. Tilton, J. H. Chen, Lead isotope systematics of three Apollo 17 mare basalts. *Proc. 10th Lunar Planet. Sci. Conf.* **1**, 259–274 (1979).
95. F. E. Jenner, H. S. C. O'Neill, Analysis of 60 elements in 616 ocean floor basaltic glasses. *Geochim. Geophys. Geosyst.* **13**, 1–11 (2012).
96. K. Lodders, B. Fegley Jr., An oxygen isotope model for the composition of Mars. *Icarus* **126**, 373–394 (1997).
97. K. Righter, K. Pando, M. Humayun, N. Waesermann, S. Yang, A. Boujibar, L. R. Danielson, Effect of silicon on activity coefficients of siderophile elements (Au, Pd, Pt, P, Ga, Cu, Zn, and Pb) in liquid Fe: Roles of core formation and a late sulfide matte in shaping terrestrial mantle geochemistry. *Geochim. Cosmochim. Acta* **232**, 101–123 (2018).
98. K. Righter, K. Pando, D.K. Ross, M. Righter, T.J. Lapen, Effect of silicon on activity coefficients of P, Bi, Cd, Sn, and Ag in liquid Fe-Si, and implications for core formation, in *Conference of the 49th Lunar and Planetary Science* (2018), 2471 p.
99. B. J. Wood, S. G. Nielsen, M. Rehämper, A. N. Halliday, The effects of core formation on the Pb- and Ti-isotopic composition of the silicate Earth. *Earth Planet. Sci. Lett.* **269**, 326–336 (2008).
100. S. G. Nielsen, N. Shimizu, C.-T. A. Lee, M. D. Behn, Chalcophile behavior of thallium during MORB melting and implications for the sulfur content of the mantle. *Geochim. Geophys. Geosyst.* **15**, 4905–4919 (2014).
101. T. Magna, U. Wiechert, A. N. Halliday, New constraints on the lithium isotope compositions of the Moon and terrestrial planets. *Earth Planet. Sci. Lett.* **243**, 336–353 (2006).
102. C. D. K. Herd, A. H. Treiman, G. A. McKay, C. K. Shearer, The behavior of Li and B during planetary basalt crystallization. *Am. Mineral.* **89**, 832–840 (2004).

**Acknowledgments:** Discussions with J. Taylor, M. Norman, S. Nemchin, and C. Neal were beneficial to interpreting some of the elemental data. **Funding:** Support for this research was provided by RTOPs from the NASA LASER and Cosmochemistry programs and NASA's Planetary Science Research Program. Lunar sample data were navigated with the aid of C. Meyer's Lunar Sample Compendium and C. Neal's Lunar List Serve Mare Basalt Database. **Competing interests:** The author declares that he has no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 12 July 2018  
Accepted 10 December 2018  
Published 23 January 2019  
10.1126/sciadv.aau7658

**Citation:** K. Righter, Volatile element depletion of the Moon—The roles of precursors, post-impact disk dynamics, and core formation. *Sci. Adv.* **5**, eaau7658 (2019).

## Volatile element depletion of the Moon—The roles of precursors, post-impact disk dynamics, and core formation

K. Righter

*Sci Adv* 5 (1), eaau7658.  
DOI: 10.1126/sciadv.aau7658

### ARTICLE TOOLS

<http://advances.sciencemag.org/content/5/1/eaau7658>

### SUPPLEMENTARY MATERIALS

<http://advances.sciencemag.org/content/suppl/2019/01/18/5.1.eaau7658.DC1>

### REFERENCES

This article cites 90 articles, 5 of which you can access for free  
<http://advances.sciencemag.org/content/5/1/eaau7658#BIBL>

### PERMISSIONS

<http://www.sciencemag.org/help/reprints-and-permissions>

Use of this article is subject to the [Terms of Service](#)

---

*Science Advances* (ISSN 2375-2548) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. 2017 © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. The title *Science Advances* is a registered trademark of AAAS.