Lunar bulk chemical composition: a post-Gravity Recovery and Interior Laboratory reassessment

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New estimates of the thickness of the lunar highlands crust based on data from the Gravity Recovery and Interior Laboratory mission, allow us to reassess the abundances of refractory elements in the Moon. Previous estimates of the Moon fall into two distinct groups: earthlike and a 50% enrichment in the Moon compared with the Earth. Revised crustal thicknesses and compositional information from remote sensing and lunar samples indicate that the crust contributes 1.13–1.85 wt% Al₂O₃ to the bulk Moon abundance. Mare basalt Al₂O₃ concentrations (8–10 wt%) and Al₂O₃ partitioning behaviour between melt and pyroxene during partial melting indicate mantle Al₂O₃ concentration in the range 1.3–3.1 wt%, depending on the relative amounts of pyroxene and olivine. Using crustal and mantle mass fractions, we show that the Moon and the Earth most likely have the same (within 20%) concentrations of refractory elements. This allows us to use correlations between pairs of refractory and volatile elements to confirm that lunar abundances of moderately volatile elements such as K, Rb and Cs are depleted by 75% in the Moon compared with the Earth and that highly volatile elements, such as Tl and Cd, are depleted by 99%. The earthlike refractory abundances and depleted volatile abundances are strong constraints on lunar formation processes.
1. Introduction

A firm knowledge of the bulk chemical composition of the Moon is important for unravelling the details of lunar origin. For example, it is well known that the Moon is depleted in volatile elements compared with the Earth, suggesting loss during lunar origin. Researchers have debated whether the Moon is enriched in refractory elements (Th, U, Zr, rare earth elements, etc.) compared with the Earth, with some authors arguing for very similar abundances [1–5] and others suggesting that the Moon is enriched in refractory elements by at least 50% compared with the Earth [5–11]. (In this paper, ‘refractory’ will be used to denote elements that condense in a gas of solar composition at temperatures greater than 1300 K at a pressure of $10^{-4}$ bar [12]. Note that condensation temperatures are only a guide to volatility as they apply to equilibrium in a gas of solar composition at low pressure, conditions vastly different from those in the hypothetical protolunar disc.)

These two drastically different views of lunar refractory abundances were driven largely by estimates of the thickness of the feldspathic crust (see §2). However, data from heat flow probes installed during the Apollo 15 and 17 missions also seemed to indicate high concentrations of U and Th, at least locally, and these measurements were used by some to also favour a global enrichment in refractory elements. Global γ-ray data from the Lunar Prospector mission helped identify the confines of the trace-element-rich province that has been named the Procellarum KREEP Terrane (PKT [9]). One of the heat-flow measurements was made in this province, with the other just exterior to it, calling into question the idea that the Moon was enriched globally in U and Th. Indeed, the asymmetric distribution of Th, as well as its unknown depth dependence, makes it difficult to determine its concentration in the crust and mantle, as seen by variations in estimates of the bulk Moon Th abundance [5,9,11,13].

In this paper, we reassess the abundances of refractory elements on the basis of revised estimates of crustal thickness derived from gravity data obtained from the Gravity Recovery and Interior Laboratory (GRAIL) mission. We conclude that the Moon is not enriched in refractory elements in comparison to the Earth. We then use the revised lunar refractory abundances and element correlations to determine the abundances of volatile elements in the bulk Moon.

2. Thickness of the crust

The thickness of the lunar crust has been revised several times since the first seismic data were analysed during the Apollo missions. These revisions were in part a result of using improved computational approaches to analyse the seismic data, but also the collection of improved topographic and gravitational data from subsequent orbital missions. In this section, we review the history of how the thickness of the lunar crust has been estimated, and then provide mass fractions of the Moon’s major geochemical reservoirs using the most recent GRAIL-derived crustal thickness models.

The initial analyses of the Apollo seismic data implied that the crust was about 55–60 km thick in the vicinity of the Apollo 12 and 14 landing sites. Toksöz et al. [14] reported a sharp seismic discontinuity in the P-wave velocity profile at 55 km depth, and a later independent analysis by Nakamura [15] obtained a concordant value of 58 ± 8 km. A study by Goins et al. [16] provided tentative evidence for a crustal thickness of 75 km in the highlands at the Apollo 16 site. These three seismic analyses were the basis of numerous bulk Moon compositional studies that were published over two decades. A summary of how measurements of the seismically determined and average crustal thickness of the Moon have evolved with time is given in figure 1.

Laser altimeter data were collected along the equatorial ground tracks of the Apollo 15 and 17 command and service modules, showing that the elevations over the nearside hemisphere were about 4 km lower than those over the farside [17]. As these large-scale variations in topography were not associated with any significant gravity anomaly, the crust should be largely isostatically compensated at these scales. If the variations in surface elevation were compensated by a crustal root (Airy compensation), the farside crust would be thicker than that of the nearside and the
average crustal thickness of the Moon would be even greater than that obtained from the seismic analyses [17]. After accounting for lateral variations in crustal density, as estimated from orbital γ-ray spectrometer data, Haines & Metzger [18] showed that the farside crust should be on average 22 km thicker than the nearside crust. In using the seismic constraint of Goins et al. [16], they reported an average crustal thickness of 73 km.

The Clementine and Lunar Prospector missions, launched respectively in 1994 and 1998, obtained the first near-global topographic maps of the Moon [19] and allowed for the construction of a vastly improved gravitation field, especially over the nearside hemisphere of the Moon [20]. With these data, it was possible to create the first global crustal thickness models by assuming densities for the crust and mantle, combined with knowledge of the crustal thickness at one locale. Neumann et al. [21] obtained an average crustal thickness of 61 km by requiring their models to match the seismically determined 55 km thickness at the Apollo 12 and 14 sites. Using an improved inversion approach, Wieczorek & Phillips [22] obtained an average thickness of 66 km with a 60 km constraint at the Apollo 12 and 14 sites. However, if the crust of the Moon were isostatically compensated by crustal thickness variations, Wieczorek & Phillips [23] showed that the relation between the lunar geoid and topography implied an average crustal thickness of 43 ± 20 km (revised to 49 ± 16 km [24]). At the low elevations of the Apollo 12 and 14 sites, the crustal thickness should have been about 28 km. Rather than call into question the accuracy of the Apollo seismic constraints, these authors instead interpreted this finding to mean that the lunar crust was stratified in density, with a low-density anorthositic layer overlying a denser noritic layer.

Two independent re-analyses of the Apollo seismic data were performed following the Lunar Prospector mission, with both suggesting that the lunar crust was considerably thinner than previously thought. Khan et al. [25] suggested that the crustal thickness was 45 ± 5 km in the Apollo zone (which is most representative of the Apollo 12 and 14 landing sites given the distribution of seismic events used in their analysis). In a subsequent analysis that tested the hypothesis of having a crust thinner than the Apollo-era analyses, they showed that models with
thicker crusts had unrealistic P-wave velocity profiles and that a crustal thickness of 38 ± 3 was preferred [26]. Lognonné et al. [10] performed an independent reprocessing of the Apollo seismic data, including the picking of new arrival times, and suggested that the crustal thickness in the Apollo zone was 30 ± 2.5 km.

Several global crustal thickness models were constructed following the revision of the Apollo seismic results. Wieczorek et al. [24] obtained an average crustal thickness of 53 km using the 45 km seismic constraint at the Apollo 12 and 14 landing sites. From a joint seismic and global crustal thickness inversion, Chenet et al. [27] found the average thickness of the crust to lie between 32 and 45 km, with a best fit value of 40 km. This study also provided seismically determined crustal thickness estimates at numerous meteoroid impact locations and provided revised crustal thicknesses at the Apollo 12, 14, 15 and 16 sites of 33 ± 5, 31 ± 7, 35 ± 8 and 38 ± 7 km, respectively. In an inversion by Hikida & Wieczorek [28], they required only that the minimum crustal thickness be less than 1 km and obtained an average crustal thickness of 43 km, with a thickness of about 40 km near the Apollo 12 and 14 landing sites. Using a similar approach, but with improved global topography and gravity models from the Kaguya mission, Ishihara et al. [29] obtained an average crustal thickness of 53 km, with a thickness of about 47 km near the Apollo 12 and 14 sites.

Almost all of the global crustal thickness models discussed above assumed that the density of the crust was somewhere between 2800 and 2900 kg m\(^{-3}\), which corresponds to the grain density of typical anorthositic rocks. High-resolution gravity data from the GRAIL mission, however, have shown that the bulk density of the lunar crust is considerably lower, 2550 kg m\(^{-3}\) [30], corresponding to a porosity of about 12%. As discussed in Wieczorek et al. [30], this porosity probably extends into the uppermost mantle. Taking into account lateral variations in crustal density as implied by remote sensing data, Wieczorek et al. [30] varied the mantle density in order to find a global crustal thickness model that fit the recent seismic constraints and that possessed minimum crustal thicknesses close to zero. The thinnest crust was found to occur beneath the Crisium and Moscoviense impact basins, precisely where remote sensing data suggest that the mantle may have been excavated [31]. When using the seismic crustal thickness constraints of 30 and 38 km at the Apollo 12 and 14 landing sites with 12% porosity in the crust, the average crustal thickness was found to be 34 and 43 km, respectively. Two additional models were constructed using a 7% porosity for the entire crust that yielded nearly identical results, but with somewhat different mantle densities.

### 3. Mass fractions of major geochemical terranes

With the GRAIL crustal thickness constraints, we calculate the mass fractions of the major lunar geochemical terranes. We report results that make use of the 30 km seismic constraint [10] with a crustal porosity of 12% and provide results for three other GRAIL models in table 1. If the radius of the core is 380 km with a density of 5200 kg m\(^{-3}\) [32], then the mass fractions of the core, mantle and crust are 1.6%, 94% and 4.4%, respectively. Based on orbital geochemical data, as well as analyses of lunar samples, the composition of the crust is known to vary among three major provinces that have distinct geologic evolutions. Following Jolliff et al. [9], these correspond to the Procellarum KREEP Terrane, the Feldspathic Highlands Terrane (FHT) and the interior of the South Pole–Aitken (SPA) impact basin. The FHT was originally divided into an inner anorthositic region and an outer, somewhat more mafic region, but we ignore this distinction here. The PKT is distinguished by having elevated abundances of the geochemical component called KREEP (for potassium, rare earth elements and phosphorous), which includes the important heat-producing elements uranium, thorium and potassium. The FHT is composed largely of anorthositic materials that are believed to represent the Moon’s primary crust that formed by flotation in a magma ocean. Finally, the interior of the SPA impact basin possesses a mafic geochemical anomaly, along with moderate enhancements in incompatible elements. The composition of this basin’s floor may represent either lower crustal materials, or a differentiated impact-melt pool [33].
The areas spanned by the three major crustal provinces, shown in figure 2, are estimated using thorium and iron abundances obtained from the Lunar Prospector γ-ray spectrometer. The PKT is here defined by those regions having more than 4 ppm Th as determined from the 2° low-altitude Th map [34]. As some regions within this province have been covered by thin layers of low thorium basalts, we also include FeO-rich regions (more than 13 wt%) where the thorium abundances are greater than 2.75 ppm. The interior of the SPA basin is defined by those regions having more than 4 ppm Th as determined from the 2° γ-ray spectrometer. The PKT and SPA basin comprise, respectively, 77.5%, 16.6% and 5.9% of the Moon’s surface area. For GRAIL model 1 (thin crust, high porosity), the average crustal thicknesses of these three provinces are 36.7, 27.9 and 20.5 km, which correspond to bulk Moon silicate mass fractions of 3.75%, 0.58% and 0.16%, respectively.

4. Al\textsubscript{2}O\textsubscript{3} concentration in the bulk silicate Moon

The most straightforward way to assess the bulk abundance of refractory elements in the Moon is to determine the contributions to the bulk lunar Al\textsubscript{2}O\textsubscript{3} abundance from the crust and mantle. We make the common cosmochemical assumption that refractory elements are not fractionated...
relative to each other. Taylor [36] discusses this concept and shows that it is reasonable in the case of Mars. Determining the bulk lunar Al₂O₃ requires knowing the masses of crust and mantle, which we report above (table 1), and the mean concentrations in the crust and mantle, which we evaluate in this section.

(a) Crust

The total abundance of Al₂O₃ in the crust depends on the relative sizes of the three major crustal terranes shown in figure 2, and on their Al₂O₃ contents. We divide each of the three terranes into three layers, though not all are necessarily present, and in some cases might be mixed. We list thorium concentrations, a refractory trace element, in each crustal column in figure 3 for reference, but do not try to compute bulk Th concentrations because the depth dependence of this element in each terrane is not easily constrained.

(i) Upper layer

A somewhat-mafic layer is exposed on the surface virtually everywhere in the highlands. Lunar meteorites [37] and orbital spectral observations [31] indicate that the uppermost crust is less feldspathic than the underlying anorthosite layer. Meteorite regolith breccias from the lunar highlands (defined as those with Al₂O₃ more than 25 wt%) average 28 ± 1 wt% (compilation of published bulk meteorite analyses taken from [38]). Global spectral reflectance data for the highlands are in the range 4–6 wt% FeO, which corresponds to 24–28 wt% Al₂O₃ using the linear inverse correlation between FeO and Al₂O₃ in lunar rocks [39]. We adopt an Al₂O₃ content of approximately 28 wt% for the upper layer. A somewhat lower value might be suitable, but this upper value maximizes Al₂O₃ in the bulk crust to test the idea of lunar refractory enrichment. Its thickness over the FHT is approximately 10 km [31], but the revised, lower crustal thickness suggests a thinner value, which we assume to be approximately 5 km. We use a thickness of between 5 and 10 km in our mass-balance calculations. Our analysis of published [40,41] remote FeO measurements suggests that it is much thinner, and probably absent, in the PKT and SPA regions. In our mass-balance calculations of Al₂O₃, we allow for up to a 5 km thickness in the PKT and SPA terranes.
Figure 3. Key parameters for the three crustal terranes. Crustal thicknesses are derived from the GRAIL crustal thickness model.

(ii) Anorthosite layer

The presence of almost pure anorthosite in basin rings [31,42] suggests that the upper somewhat-mafic layer is underlain by a substantial thickness of anorthosite. Spectral data indicate that the anorthosite contains less than 2 wt% FeO, corresponding to more than 31 wt% Al$_2$O$_3$, and contains no detectable mafic silicates. We assume an Al$_2$O$_3$ content of 34 wt% to account for the presence of at least some olivine and pyroxene in the anorthosites as shown by Apollo samples [43]; for comparison, pure anorthite contains approximately 36 wt%. Anorthosite occupies most of the crustal column in the feldspathic highlands (figure 3), with its thickness depending on the thickness of layers above and below it, and on the total crustal thickness. Sample studies suggest that anorthosite is rare, but not absent in the PKT (anorthosites were collected at the Apollo 15 site), so we allow for an anorthosite layer up to 5 km thick in that terrane. Remote sensing observations do not unequivocally identify anorthosite in the SPA except in its outermost regions, but we allow for a layer of 5 km thick, recognizing that it could be essentially absent.

(iii) Mafic lower layer

It is plausible that a more mafic layer resides below the anorthosite layer, as first argued by Ryder & Wood [44] on the basis of the compositions of mafic impact melt breccias of the type ‘LKFM basalt’ (low-K Fra Mauro [45]) collected at the Apollo 15 and 17 landing sites. Using LKFM impact melt rocks as a guide, we estimate that the layer contains approximately 19 wt% Al$_2$O$_3$. Based on the abundance of LKFM at the landing sites in the PKT, including in ejecta from small and large craters, it seems likely that most of the crustal column in the PKT is composed of rock with such basaltic compositions [9]. We assume that mafic rock dominates the crust in the SPA basin, too, though with different abundances of incompatible elements.

We wish to calculate the total contribution the crust makes to the bulk lunar composition of refractory elements. The four models shown in table 1 (corresponding to the four GRAIL crustal thickness models [30]), combined with the three layers possible in each terrane (figure 3 and above discussion) result in a large combination of possible Al$_2$O$_3$ concentrations, so we present the lowest and highest values. The lowest (1.13 wt%) is obtained for the case of model 1 (thinnest crust...
Figure 4. Estimate of $\text{Al}_2\text{O}_3$ in the mantle mare basalt source regions. Curves are shown for mare basalt magmas with 9 and 10 wt% $\text{Al}_2\text{O}_3$ and for 5% and 10% partial melting. The horizontal axis shows the ratio of pyroxene to total mafic silicates. The more pyroxene in the source, the higher the $\text{Al}_2\text{O}_3$ because it partitions into pyroxene in preference to olivine. Using the lowest and highest $\text{Al}_2\text{O}_3$ values on the lines, we infer that the mantle contributes between 1.3 and 3.1 wt% to the bulk lunar $\text{Al}_2\text{O}_3$ content.
Figure 5. Contributions to bulk Moon abundance of $\text{Al}_2\text{O}_3$ as a function of $\text{Al}_2\text{O}_3$ in the mantle and crust. Crustal contributions from consideration of models 1–4 (table 1) and thicknesses of lithologic layers (figure 3) range from 1.13 to 1.85 wt% $\text{Al}_2\text{O}_3$. Mantle concentrations are from figure 4. Dark lines represent 1.0 and 1.5 times the Earth abundance, with light lines showing increments of 0.1. The full range of possibilities for crustal and mantle concentrations of $\text{Al}_2\text{O}_3$ straddle the line for which bulk lunar $\text{Al}_2\text{O}_3$ is the same as in the bulk Earth. Strong enrichment relative to the Earth is ruled out, although enrichments of 10–20% are possible.

[49] based on multiple-saturation experiments. These depths may be minima due to possible formation at a range of pressures and to fractional crystallization during migration to the lunar surface [51], so the mare basalt source regions could perhaps be representative deeper parts of the mantle. Some analyses of the Apollo seismic data are consistent with the mantle not having any seismic discontinuities [50,52], suggesting a uniform composition. Nevertheless, the composition of the lower mantle is uncertain, so it is worth examining how a reasonable range in $\text{Al}_2\text{O}_3$ concentrations would affect the bulk mantle, and hence bulk Moon, composition.

If the core is 380 km in radius, the crust is 34 km thick and the upper mantle extends to 500 km beneath the base of the crust, the lower mantle would constitute 35% of the total mantle. If the lower mantle contains 6 wt% $\text{Al}_2\text{O}_3$ (the bulk Moon abundance if the Moon is enriched in refractory elements by 50%), the mantle contribution to the bulk Moon would be 2.9–4.1 wt% for an upper mantle $\text{Al}_2\text{O}_3$ of 1.3–3.1 wt%, respectively. As can be inferred from figure 5, the upper part of this range could indicate a refractory-enriched Moon, although not enriched by 50%. In the more likely case that the lower mantle contains 4 wt% $\text{Al}_2\text{O}_3$, the amount in the bulk silicate Earth [46–48], the total mantle contribution changes from 1.3 to 3.1 wt% to 2.2 to 3.4 wt%, not significantly different from the ranges shown in figure 5. Finally, the lower mantle could be depleted in $\text{Al}_2\text{O}_3$ if a large fraction of the initial, deep cumulates from the magma ocean did not rise to higher levels during mantle overturn. If the lower mantle contains only 1 wt% $\text{Al}_2\text{O}_3$, the mantle contribution would drop to 1.2–2.4 wt%, making a firmer case for no enrichment relative to the Earth.

(c) Bulk silicate Moon

We combine the crustal and mantle contributions in figure 5. The intersection of the mantle and crust ranges defines the probable lunar composition. The negative-sloping heavy lines represent the expected relations for bulk compositions exactly like that of Earth and 1.5 times terrestrial.
values; lighter lines represent increments 0.1 times terrestrial abundances. The line representing no enrichment relative to the Earth roughly bisects the box defined by our estimates of Al$_2$O$_3$ in the crust and mantle, indicating that it is likely that the Moon is not enriched in Al and by inference other refractory elements compared with the Earth. Nevertheless, the data allow for a modest enrichment or depletions of up to ±20% (relative), which we take as an estimate of the uncertainty of the estimate. When the crust was thought to be thicker and more aluminous than our analysis indicates (more than 2.5 wt% Al$_2$O$_3$), enrichment relative to the Earth was far more likely.

The similar aluminium abundances in the Earth and the Moon indicate that processes during formation of the Moon did not cause discernible enrichment of refractory elements in the Moon. This is not the case for volatile elements as shown below.

5. Absolute abundances of volatile elements

Volatile elements are informative about planetary formation and the source materials for the planets. In the case of the Moon, they might hold especially useful information about the processes involved in formation of the Moon. As noted above, refractory elements have condensation temperatures greater than 1300 K (at a pressure of 10$^{-4}$ bar [12]). The condensation temperature is really the temperature at which half the mass of an element is in the solid and is properly called the 50% condensation temperature. Moderately volatile elements (e.g. K and Rb) have 50% condensation temperatures in the range 1230–800 K; highly volatile elements (e.g. Tl and Cd) have condensation temperatures in the range 750 K (Bi) to 530 K (Tl). (Hg has a 50% condensation temperature of only 250 K, but far fewer measurements of Hg concentrations are available than for the other highly volatile elements.)

If our model is correct and the Moon has terrestrial abundances of refractory elements, then we can determine the absolute abundances of volatile elements. We do this by searching for correlations between two elements with very similar geochemical behaviour, one refractory and the other volatile. For example, we can establish the K concentration in the Moon by its correlation with an incompatible refractory element such as La or Th. If the correlation is strong, we multiply the ratio of the volatile to the refractory element (e.g. K/La) by the abundance of the refractory, assuming that the lunar refractory abundance is the same as in the Earth. For terrestrial values, we have used those determined by McDonough & Sun [47]. For comparisons between refractory and volatile incompatible elements (these concentrate in magma in preference to major minerals), it is useful to use as wide a range in element concentrations as possible. Thus, we use concentrations in mare basalts (mostly low concentrations) and KREEP basalts (high concentrations) to define the volatile/refractory element ratio most reliably. Although ferroan anorthosites and Mg-suite rocks contain useful information as well, their cumulate nature masks the incompatible behaviour of trace elements. In addition, far fewer highland rocks have been analysed for volatile trace elements.

The alkali elements K, Rb and Cs in mare and KREEP basalts are plotted against La in figure 6. In spite of the scatter at low concentrations, the linear fits are impressive because of the large range in concentrations and large number of data points. The correlations and the terrestrial bulk La value (0.648 ppm) allow us to estimate the bulk concentrations in the Moon (table 2). Uncertainties are calculated from the quality of the fit using the York method [54]. The 2-$\sigma$ uncertainties for the Moon/Earth ratios incorporate the uncertainties in the terrestrial values [47]. Other moderately volatile elements do not have strong correlations with a refractory element.

The highly volatile elements Tl (figure 7) and Cd are incompatible and correlate with the incompatible refractory element La ($R^2$, the square of the correlation coefficient, is 0.9 and 0.6, respectively). Br correlates adequately with Tl. It would be preferable to determine the Br abundance from a refractory element rather than Tl, which is already an estimate from its correlation with La, but no such correlations were observed. Bi is an incompatible element, but it does not correlate well ($R^2 < 0.5$) with any refractory element. We estimate its abundance by determining its ratio with Th, using the mean abundance in rocks where both have been
Figure 6. Correlations of incompatible volatile alkali elements with incompatible refractory La. Knowing that refractory elements are similar in the Earth and the Moon allows us to determine K, Rb and Cs concentrations in the bulk Moon. The quality of the linear fits to the data ($R^2$ values) decrease with decreasing concentration, perhaps indicating greater analytical uncertainty, particularly for Cs. Data from [53].

Table 2. Concentrations of moderately volatile and volatile elements in the bulk silicate Moon.

<table>
<thead>
<tr>
<th>element</th>
<th>temp. (K)$^a$</th>
<th>conc.</th>
<th>2-$\sigma$</th>
<th>method$^b$</th>
<th>ratio$^c$</th>
<th>Moon/Earth</th>
<th>2-$\sigma$</th>
<th>Moon/Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (ppm)</td>
<td>1006</td>
<td>36.9</td>
<td>0.9</td>
<td>S</td>
<td>K/La</td>
<td>0.205</td>
<td>0.01</td>
<td>0.068</td>
</tr>
<tr>
<td>Rb (ppm)</td>
<td>800</td>
<td>0.13</td>
<td>0.005</td>
<td>S</td>
<td>Rb/La</td>
<td>0.24</td>
<td>0.02</td>
<td>0.056</td>
</tr>
<tr>
<td>Cs (ppb)</td>
<td>799</td>
<td>5.0</td>
<td>0.3</td>
<td>S</td>
<td>Cs/La</td>
<td>0.28</td>
<td>0.03</td>
<td>0.026</td>
</tr>
<tr>
<td>Sb (ppb)</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>S</td>
<td>Sb/Tl</td>
<td>0.003</td>
<td>0.003</td>
<td>0.00013</td>
</tr>
<tr>
<td>Bi (ppb)</td>
<td>746</td>
<td>0.02</td>
<td>0.006</td>
<td>A</td>
<td>Bi/Th</td>
<td>0.008</td>
<td>0.007</td>
<td>0.00018</td>
</tr>
<tr>
<td>Zn (ppm)</td>
<td>726</td>
<td>0.40</td>
<td>0.15</td>
<td>A</td>
<td>Zn/Sc</td>
<td>0.007</td>
<td>0.004</td>
<td>0.0013</td>
</tr>
<tr>
<td>Cd (ppb)</td>
<td>652</td>
<td>0.31</td>
<td>0.14</td>
<td>S</td>
<td>Cd/La</td>
<td>0.009</td>
<td>0.004</td>
<td>0.00055</td>
</tr>
<tr>
<td>Br (ppb)</td>
<td>546</td>
<td>0.79</td>
<td>0.05</td>
<td>S</td>
<td>Br/Tl</td>
<td>0.019</td>
<td>0.01</td>
<td>0.00274</td>
</tr>
<tr>
<td>Tl (ppb)</td>
<td>532</td>
<td>0.030</td>
<td>0.004</td>
<td>S</td>
<td>Tl/La</td>
<td>0.010</td>
<td>0.005</td>
<td>0.00025</td>
</tr>
</tbody>
</table>

$^a$50% condensation temperature at $1 \times 10^{-4}$ bars [12].

$^b$S indicates use of slope of correlation line. A indicates average of ratio of abundances to another element.

$^c$Ratio indicates elements used to determine volatile element abundance.

measured. Zn is a weakly incompatible to compatible element with behaviour similar to Sc (in the absence of sulfide phases), so we estimate its abundance by taking the ratio of the average concentrations of Zn and Sc.

Lunar abundances of selected refractory and volatile elements are shown in figure 8 and table 2. We normalize them to terrestrial values as this is most informative about lunar formation by a giant impact. Though normalization to CI chondrites could be useful, planets do not necessarily have CI abundances of volatile elements, making it difficult to track changes in
Figure 7. Incompatible highly volatile element Tl plotted against incompatible refractory element La in lunar mare and KREEP basalts. La from [53]; Tl from [55–58]. $R^2$ values are high, but driven by the highest values on the plot.

Figure 8. Abundances of volatile elements in the Moon, normalized to terrestrial abundances. Refractory elements shown for reference and assumed to be the same as in the Earth. Lunar depletions compared with the Earth are 0.24 for moderately volatile K, Rb and Cs, and 0.01 for highly volatile elements (values are geometric means). Uncertainties for refractory and moderately volatile elements are within the symbols.

Their abundances during formation of the Moon. As has been known since early analysis of Apollo samples, lunar abundances of volatiles are depleted relative to the Earth abundances. The moderately volatile elements are curiously inversely related to their condensation temperatures, but not strongly so (figure 8). Their mean abundance is 0.24 times the Earth. The alkalis are progressively depleted in order of condensation temperature when normalized to CI chondrites (table 2).
The highly volatile elements are severely depleted [55]. The geometric mean of their Earth-normalized abundances is 0.01. Although the uncertainties are high, there is a hint of an inverse relation with condensation order, as observed for the alkali elements. Additional analyses of lunar samples are needed to establish whether this weak trend is statistically significant or not. It is possible that the highly volatile elements are uniformly depleted relative to the Earth. Wolf & Anders [55] and Taylor et al. [11] drew attention to the uniformity in CI-normalized concentrations in a large suite of low-Ti mare basalts, but did not determine abundances by element correlations. Our results indicate that CI-normalized abundances among the highly volatile elements differ by close to a factor of 10. By contrast, Earth-normalized abundances are similar to each other, although present at only 1% of terrestrial abundances.

6. Implications for lunar origin

On the basis of revised crustal thicknesses from GRAIL, our model calculations indicate that refractory elements are not enriched in the Moon compared with their abundances in the bulk silicate Earth. The similarity in abundances of refractory elements implies that processes in the protolunar disc did not lead to relative fractionation of refractory elements or to a general enrichment during condensation and partial crystallization of the disc before the Moon accreted from it. Chemical models of disc processes [59–61] need to account for the approximate similarity with terrestrial abundances of refractory elements.

The volatile elements might allow us to constrain processes in the protolunar disc after a giant impact, ignoring the possibility that volatiles could have been lost from the magma ocean after the Moon formed. The moderately volatile elements have lunar concentrations only about 25% (table 2 and figure 8) of their concentrations in the Earth. Assuming that most of the material making up the Moon derived from the Earth, then 75% of the initial concentrations of moderately volatile elements were lost during the Moon-forming impact and subsequent evolution of the protolunar disc. About 99% of the highly volatile elements were lost during lunar formation, with little fractionation among them. Thus, there appears to be a rough correlation of percentage loss with volatility (moderately volatile versus highly volatile elements), but losses within each group were accompanied by only limited fractionation of one element from another. Preliminary results [62,63] address volatile loss from the protolunar disc through a combination of mixing with the proto-Earth (similar to that proposed by Pahlevan & Stevenson [59]) and subsequent hydrodynamic escape of the volatile-rich vapour portion of the disc. The concentrations of volatiles in the Moon would depend on their solubility in the magma portion of the protolunar disc (assuming minimal loss from the magma ocean).

The discovery of H components (H2, OH and H2O) in the lunar interior [64] adds another dimension to the picture of lunar volatiles. H components are even more volatile than the highly volatile elements, yet may be present in higher abundance than the volatile elements. For example, estimates for the concentrations of H components (expressed as equivalent H2O) in the source regions of pyroclastic glasses [65] and mare basalts [66] are approximately 100 ppm. These are similar to terrestrial Mid-Ocean Ridge basalt (MORB) source regions, 80–180 ppm [67], and about 20% of minimum bulk Earth concentration [68]. (Enriched MORB mantle sources have higher H2O concentrations, 200–950 ppm [67].)

Volatile elements and H2O are not well correlated. In spite of the overall strong depletion of volatile elements in the Moon, pyroclastic glasses have concentrations of highly volatile elements that are close to those in MORBs. By contrast, low-Ti mare basalts, many of which appear to have similar H2O concentrations as do the pyroclastic glasses, have only 1% of terrestrial abundances of highly volatile elements. It appears that H components and highly volatile elements are decoupled. Whether the lack of correlation between H components and volatile elements is due to the nature of the impactor (e.g. ice-rich), early additions to the Moon, or processes inside the complicated and evolving protolunar disc is not yet known. An additional complication is that H concentrations do not appear to be uniform inside the Moon, as shown by the significantly lower...
H₂O concentrations in rocks related to KREEP basaltic magmas [69], including KREEP basalts and Mg- and alkali-suite rocks.

The details of lunar formation have not been worked out thoroughly, but all models need to satisfy central geochemical properties of the Moon: similar abundances of refractory elements in Moon and the Earth, and lunar depletion in moderately (25% compared with the Earth) and highly (1% compared with the Earth) volatile elements. Still to be determined are the details of the depletions and volatile element distributions (including H components) in the lunar interior.

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