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An asteroidal origin for water in the Moon

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The Apollo-derived tenet of an anhydrous Moon has been contested following measurement of water in several lunar samples that require water to be present in the lunar interior. However, significant uncertainties exist regarding the flux, sources and timing of water delivery to the Moon. Here we address those fundamental issues by constraining the mass of water accreted to the Moon and modelling the relative proportions of asteroidal and cometary sources for water that are consistent with measured isotopic compositions of lunar samples. We determine that a combination of carbonaceous chondrite-type materials were responsible for the majority of water (and nitrogen) delivered to the Earth–Moon system. Crucially, we conclude that comets containing water enriched in deuterium contributed significantly <20% of the water in the Moon. Therefore, our work places important constraints on the types of objects impacting the Moon ~4.5–4.3 billion years ago and on the origin of water in the inner Solar System.
Lunar sample studies have focused on the measurement of H (reported as equivalent amounts of OH or H$_2$O) in lunar volcanic glass beads$^{1-3}$, melt inclusions$^{4,5}$ andapatite in lunar basalts and highlands samples$^{2-8}$. From this compilation of work the bulk silicate Moon (BSM) is estimated to contain between $\sim$10 and 300 p.p.m. H$_2$O$^{9,10}$. A few of these studies reported the identification of a primordial H-isotopic signature$^{2-7}$, corresponding to Earth-like $\delta$D values between $\sim -200$ and $\sim +1800$‰ (where $\delta$D = ([D/H]$^\text{sample}$/[D/H]$_{SMOW}$ - 1) x 1000; SMOW: standard mean ocean water). Therefore, the similar nature of water (the term water is hereafter used to refer to H$_2$O equivalent) in the Earth and Moon suggests that water locked up inside of the Moon was either inherited directly from the proto-Earth or delivered to the Earth–Moon system shortly after the formation of the Moon (Fig. 1) through impacting carbonaceous chondrite (CC)-type asteroids, since bulk D/H ratios for most CC-types$^{11}$ are consistent with those of terrestrial$^{12,13}$ and lunar water (Fig. 2).

Models for the differentiation of the Moon invoke the presence of a lunar magma ocean (LMO) and place the lifetime of this LMO to between $\sim$10 and 200 Ma after the Moon-forming event (as reviewed by Elkins-Tanton et al.$^{14}$), which necessitates that volatile accretion occurred relatively early in the Moon’s geological history (Fig. 1). The final dregs of the LMO, enriched in incompatible elements such as potassium (K), rare-earth-elements (REEs) and phosphorous (P)—collectively termed urKREEP—should have contained the vast majority of the lunar water, as OH would have been incompatible in the crystallizing mantle cumulates and the crust$^{10}$. Lunar samples with a significant KREEP component, such as Mg-suite rocks and KREEP basalts$^{7,8}$, are characterized by H-isotopic compositions that are similar to those estimated for the mantle source regions of picritic glasses and mare basalts$^{2,3,6}$, suggesting that the crystallization of the LMO did not result in significant fractionation of the H isotopes of water. To retain volatiles in the LMO, a conductive lid is required, to have prevented significant loss of water via degassing of H-bearing species, and is consistent with the formation of an early anorthosite crust a few kilometres thick in the first few thousand years of the Moon’s history$^{14}$. It is likely that the lunar crust then grew by continuous underplating of more anorthositic materials over a period of between $\sim$10 and $\sim$200 million years until the LMO completely solidified, leading to the mantle cumulate overturn (see review by Elkins-Tanton et al.$^{14}$). This time period between lunar accretion and the overturn of mantle cumulates permits any water (and other volatiles) accreted to the LMO to be incorporated into the mantle source regions of mare basalts and picritic glasses ($\sim$100 km deep$^{15}$), and the urKREEP liquid provided that impactors were able to breach the lunar crust. Crystallization of an insulating crust likely started only after $\sim$80% LMO crystallization$^{14}$. During its initial growth the crust was likely hot and tenuous and perhaps even re-melted if tidal heating played an important role$^{14}$, meaning not only that impactors could have reached the LMO melt pool but also that many early impact structures could have been erased during crustal underplating and modification. Therefore, volatile delivery through the earliest lunar crust into the LMO could have balanced out any potential loss of volatiles (accreted or indigenous) by degassing (before 80% solidification).

Studies that have modelled the flux of impactors to the Moon posit that it was likely that the time period between lunar accretion and differentiation received relatively fewer impact events than during the late heavy bombardment (LHB) (for example, Morbidelli et al.$^{16}$), but importantly this was not a quiescent time. Indeed, there are $\sim$12 preserved Pre-Nectarian lunar basins that have excavations depths around or greater than 34–45 km (ref. 17), which corresponds to the current estimates for lunar crustal thickness based on observations by the GRAIL spacecraft$^{18}$. This demonstrates that large impacts occurred early in the Moon’s history (albeit infrequently compared with the LHB epoch$^{19}$). In summary, the time interval for water delivery to the LMO, hereafter referred to as the late accretion window ‘LAW’, is conceptually restricted to between time zero (Moon formation) and up to $\sim$200 Ma thereafter. Importantly, the bulk of lunar water was delivered during LAW, which is distinct from a much younger basing-forming epoch on the Moon that is commonly referred to as the LHB, lunar cataclysm, or inner Solar System cataclysm$^{16,20-22}$.

It has been suggested that water could have been accreted together with the Moon-forming material in the so-called ‘cold start’$^{9}$. Whilst it is plausible that some water may have been retained since the Moon’s formation$^{23}$, it is highly unlikely that all of BSM water (up to 300 p.p.m. H$_2$O) was accreted in this manner and survived LMO processing. Therefore, we envisage two scenarios that can account for the bulk water inventory of the Moon, the first that water was accreted solely during the LAW and no water was inherited from the Moon-forming material (scenario 1), and the second that a portion (we consider up to 25%) of the BSM water was accreted with Moon-forming materials and was then supplemented by water delivery during the LAW (scenario 2).

![Figure 1](https://example.com/fig1.png)

**Figure 1** Cartoon showing the possible time windows and scenarios for the accretion of volatiles to the lunar interior. Volatiles were accreted to the Moon during its formation (a) and/or continuously delivered by impacting bodies during the ca. 10–200 million years of crystallization of the lunar magma ocean (b). This graphic is not to scale.
In this study we utilize estimates of the water content of the BSM4,9,10 and its H-isotopic composition11,54 together with the current database for the bulk water contents of chondritic meteorites (Table 1, see Methods section), to determine the amount of water added to the early Moon by impacting objects. We consider a range of possible accretion scenarios during LAW to investigate the implications for the mass of water accreted and populations of accreting objects. This is constrained by the estimates for the proportion of lunar mass that was likely added post-lunar core-formation from studies of highly siderophile elements (HSEs) in lunar basalts (up to 0.02% lunar mass24,25) and highly volatile elements in mare basalts and picritic glasses (up to 0.4% lunar mass4,9). Our results indicate that carbonaceous chondrite types of impactors were the most important contributors of water to the lunar interior and that comets (with heavy water, Fig. 2) played a very small role.

**Results**

**Mass of asteroidal materials added during the LAW.** Based on the BSM water estimates of McCubbin et al.10 (~10–100 p.p.m. H2O), and Chen et al.4 and Hauri et al.9 (~100–300 p.p.m. H2O), we have calculated the amount of material supplied by chondritic impactors to accrete ~10, 100 and 300 p.p.m. bulk H2O for LMO depths of 400 and 1,000 km (to match the various LMO depths estimated in previous studies13,14,16,27), and have recast these estimates into the context of how much lunar mass each would represent (Table 2 and Fig. 3). The types of carbonaceous chondrites are defined in the caption accompanying Fig. 2.

In scenario 1, for example, between 3.94 × 1016 kg (~1 p.p.m. H2O) and 2.05 × 1017 kg H2O (~52 p.p.m. H2O) could have been accreted by CI-type CCs into a 400-km-deep LMO to remain below the addition threshold of <0.02% lunar mass (Table 1). In fact, using this <0.02% lunar mass threshold prohibits the addition of 300 p.p.m. H2O by asteroids alone (Table 2). On the other hand, the accretion of up to 0.4% lunar mass in some cases, allows for the addition of H2O in amounts greater than the high-end of BSM H2O estimates (Table 2).

Importantly, because equilibrated ordinary (OC) and enstatite chondrites (EC) contain very little water (Table 1) the mass of such types of chondritic material added to accrete even 10 p.p.m. H2O greatly exceeds the mass constraints imposed by HSE and highly volatile element abundances (Table 2). As a consequence, although ECs are considered an ideal geochemical match for the BSM and the bulk silicate Earth, and Os isotope signatures may suggest a large contribution of OC- and EC-type objects in materials accreted to the Earth–Moon system during late accretion8,29, it is clear that these types of objects are unlikely to have contributed significant amounts of H2O to the lunar interior. The accretion during the LAW of CC material is consistent with the impact of CC-type asteroids during the LHBE. HSE data have been interpreted to mean that EC and OC impactors also played an important role during the LHBE30,31, which may reflect a change in impactor populations over the first ~500 million years of the Moon’s evolution and, thus, dynamical mixing of material in the Solar System. The same data have also been interpreted, however, to represent a mixture of OC and CC impactors together with differentiated iron impactors9–12,32, in which case CC asteroids remained an important source of impactors.

**Assessing the contribution of cometary water during LAW.** The first scenario in this study assumes that the Moon accreted completely dry or that any primordial water was completely lost very early in the Moon’s history, and that late-accretion delivered all of the water in the BSM. Considering a BSM of 100 p.p.m. H2O (the most recent BSM water estimates overlapping at this

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**Figure 2 | Hydrogen isotope signatures for different objects in the Solar System.** The grey bar indicates the range of δD values predicted for the lunar interior based on the previous studies of water and its H-isotopic composition in lunar samples2,3,6–8. (a) The H-isotopic compositions of comets, where the data for comets 1P/Halley60, Hyakutake61, Hale-Bopp62, C/2002 T7 (ref. 63), C/2009 P1 (ref. 64), 8P/Tuttle65, and 153P/Ikeya-Zhang66, 45P/Honda-Mrkos-Pajdusakova57, 103P/Hartley 2 (ref. 56) and 67P/Churyumov-Gerasimenko58. (b) The H-isotopic composition of apatite grains from eucrites47, and the range in values for interplanetary dust particles (IDPs)67,68. (c) The bulk H-isotopic data for bulk Tagish Lake (TL) and other carbonaceous and ordinary chondrites (CC and OC, respectively)11,55. (d) The H-isotopic compositions of martian meteorite groundmass46,47, martian meteorite mantle46 and mantle crust and mantle46,73–75. (e) Data for lunar apatite5–8,33,47,77, lunar picritic glasses5,11 and olivine-hosted melt-inclusions in picritic glasses67. (g) The range in H-isotopic compositions of H2O on Earth12,13,78. (h) The H-isotopic composition of Proto-solar and interstellar medium42. For carbonaceous chondrites, CI, CM-, CV-, CO- and CR- refer to the different groups, named according to one prominent meteorite of the group, respectively Ivuna, Mighei, Vigorano, Ormons and Renazzo. OC stands for ordinary chondrites. Error bars indicate measured analytical uncertainties, please see original references for more information (Enceladus, Jovian planets, and comets error bars, 1 s.d., and Eucrite data, 2 s.d.).
isotopic limits (2,3,6–8), and reached a final BSM water content of 1% and 25% of the total amount of water added from a cometary source.

In scenario 2, we consider that the Moon accreted with 1% H₂O is allowed from D-enriched Kuiper belt (DEK) comets (Table 3). Mixing of cometary water with predominantly CV-, CM- or CO-type CCs, respectively, also result in minor cometary contributions of 1% from Oort cloud-like objects (Fig. 4 and Table 3).

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of water (H$_2$O), $D_i$ refers to the initial H-isotopic composition of the water in the LMO, H$_2$O$_{LA}$ refers to the mass of water added during LAW (kg), $f_{H_2O}$ is the proportion (fraction of amount added during LAW) of water accreted by a given type of impactor denoted with A or B, respectively, and all other parameters are the same as in equation (1).

Mixing of water from CI-type CCs with water from CO, CM, CV-type CCs and DDK comets in different proportions can yield final δD values < +100‰ (Table 3), satisfying isotopic constraints. If deuterium-enriched comets were involved in the addition of water during LAW then up to ~14% H$_2$O could have originated from Oort cloud-type comets and ~5% H$_2$O from DEK comets if the remaining water is assumed to come from CI-type chondrites (Fig. 5a), proportions that increase to ~7 and ~19% H$_2$O originating from DEK and Oort cloud comets, respectively, if the remaining water came from CM-type chondrites (Fig. 5b and Table 3). Significantly, in the case where CO-type CCs dominated the impactor population (Fig. 5c) up to ~27% H$_2$O could have been contributed by Oort cloud-like comets and up to ~10% H$_2$O from DEK comets (Table 5). In addition, we considered that the LMO underwent some degassing before prior to late addition (see Methods section) and found that the results limit the amount of initial water present before late addition (assuming degassed H-isotopic composition of ~ +800‰ (ref. 8)), which further restricts the amount of water contributed by D-rich comets (Table 4).

### Discussion
To a first order, a dominantly asteroidal source of water accreted during the LAW is similar to the dominant source inferred for the subsequent basin-forming epoch of the Moon, based on geochemical and mineralogical markers, implying that asteroids and not comets dominated the impactor population hitting the Moon during its first 500 million years of geological history. Although the source of objects delivered to the Earth–Moon system may have largely remained the same, the dynamical delivery could have been much different, as the basin-forming epoch appears to have been characterized by asteroids with higher impact velocities compared with those during the early accretional epoch (LAW) (Bottke et al., and references therein). We note that the accretion of CC-type material during

![Figure 3](image-url)  
**Figure 3** | Mass of chondritic material added during late accretion compatible with BSM water estimates. This figure shows the mass of the different types of chondritic material accreted (kg) to the Moon to add 10 (circles), 100 (squares) and 300 p.p.m. H$_2$O (diamonds), respectively, to a 400-km-deep LMO, and the corresponding amount in terms of lunar mass. The mass constraints imposed by HSE (0.02% lunar mass added) and highly volatile element abundances (up to 0.4% lunar mass added) are indicated by the dashed lines. Where: CI-type carbonaceous chondrites (CCs) are Ivuna-like, CO are Ornans-like, CV are Vigorano-like, CM are Mighei-like and CR are Renazzo-like, respectively.

![Figure 4](image-url)  
**Figure 4** | An example of a two-component mixing model for scenario 1 considering that CI type CCs were dominant during the LAW. This model assumes 100 p.p.m. H$_2$O in BSM, equivalent to 3.94 × 10$^{18}$ kg of H$_2$O for a 400-km-deep LMO. The plot shows the resultant δD value and D/H ratios of the water mixture versus the amount of water (kg) supplied by CI-type carbonaceous chondrites as an example (results in Table 3). The bar underneath the x-axis shows how the mass of water is related to % of water mixed. Only final H-isotopic compositions below +100‰ (denoted by the blue box) are acceptable within the constraints of the model (see Methods). Where: CI-type carbonaceous chondrites (CCs) are Ivuna-like, CV are Vigorano-like, CO are Ornans-like, CM are Mighei-like and CR are Renazzo-like, respectively. Note that it only takes a couple of per cent contribution of water from Oort or DEK comets to produce H-isotope compositions outside of the model limits. DDK, deuterium-depleted Kuiper belt comets; DEK, deuterium-enriched Kuiper belt comets; Oort, average H-isotopic composition of Oort cloud comets.

<table>
<thead>
<tr>
<th>Major CC type</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% H$_2$O from DEK comets</td>
<td>% H$_2$O from Oort-like comets</td>
</tr>
<tr>
<td>CI</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>CM</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>CO</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>CV</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>

Max., maximum; LL initial, lower limit (1% BSM H$_2$O) of H$_2$O initially in lunar magma ocean; UL initial, upper limit (25% BSM H$_2$O) of H$_2$O initially in the lunar magma ocean. Showing the maximum proportions (%) of water permitted from deuterium-enriched Kuiper belt (DEK) and Oort cloud comets assuming the rest of lunar water was delivered by CC-type asteroids.

Table 3 | Results from mixing models of scenario 1 and 2.
Figure 5 | Two-component mixing models for scenario 2 considering that CI or CM or CO-type CCs dominated the impactor population during the LAW. The resultant $\delta D$ value of each water mixture (‰) versus the amount of water (kg) supplied by (a) CI-, (b) CM- and (c) CO-type carbonaceous chondrites. Table 3 also gives results from mixes with CV-type CCs. This model assumes that the LMO initially contained between 1% (dashed black lines) and 25% (solid black lines) of the BSM water (100 p.p.m. H$_2$O) with a $\delta D$ value of $-200$‰. Only final H-isotopic compositions $\leq +100$‰ are acceptable within the model constraints (denoted by the black boxes). Where: CI-type carbonaceous chondrites (CCs) are Ivuna-like, CO are Ornans-like, CV are Vigorano-like, CM are Mighei-like and CR are Renazzo-like, respectively.
the LAW, that is required to account for the lunar H-isotope and water abundances in the lunar interior, is distinct from a late veneer dominated by EC- and OC-type objects that has been inferred from Os isotope studies of terrestrial rocks13,28,29. This dichotomy could imply that either the largest impactors that preferentially impacted the Earth due to stochastic accretion19 were OC- and EC-type objects, while the population of smaller impactors included abundant CC objects that preferentially impacted the Moon, or that while the accreting objects had OC- and EC-type Os isotope signatures, they had CC-type water abundances and H-isotope signatures, consistent with other evidence that support the presence of planetesimal-types that are not represented in modern meteorite falls36.

On the basis of combined N isotopes and N/C ratios, the lunar interior seems to be best matched with CO-type CCs37. In terms of N, we can estimate the amount of N delivered to the LMO based on our calculations of the mass of chondritic material added during LAW for each chondrite type (Table 2, restricted to consideration of material added to achieve a BSM with ~100 p.p.m. H2O), and the average N contents in the different chondrite types (Table 1). Results yield N contents for the BSM of ~0.95 to 2.21 p.p.m. for LMO depths of 400 and 1,000 km (Table 5), which is consistent with an average of ~1 p.p.m. N in the lunar mantle as estimated by Furi et al.38. If minimal fractionation of 15N/14N occurred during basalt ascent and eruption38,39, then the N-isotopic composition measured in mare basalts of between ~ −2 and +27% (refs 37,38) should reflect the isotopic composition of the lunar mantle source regions from which the basalts were derived. If all of the N in the LMO was added during LAW (scenario 1) then mixing of CI-, CM-, CO- and CV-type CCs provide suitable matches for the origin of lunar N (Methods section and Table 1) and restrict cometary contribution of N to as much as ~5% (Table 5). This is comparable to scenario 2, where considering the lowest mare basalt δ15N value of ~ −2% (ref. 37) to represent the N-isotopic signature of N accreted with Moon-forming materials before LAW, then up to ~6% N could have been delivered by comets (Table 5). Still using scenario 2 but considering that the isotopic signature of N accreted when the Moon formed was consistent with that of the primordial Earth mantle, which is thought to be as low as ~ −40% (reviewed by Furi and Marty40), increases the possible cometary contribution to a maximum of ~8% of total lunar interior N.

Therefore, it appears that in order to add the appropriate amounts of H2O and N to the lunar interior during LAW, while keeping the H- and N-isotopic compositions in line with sample measurements, requires the contemporaneous accretion of the various types of CCs (mostly CO, CI, CM and CV), together with < ~20% cometary input.

The very-low apparently indigenous lunar δD values of ~−600‰ reported by Robinson et al.41 are quite anomalous. In fact, such low values have yet to be observed in terrestrial rocks, the lowest δD values being ~−220‰ for Earth’s depleted upper mantle13. Therefore, such low values reported for an intrusive lunar rock42 could potentially indicate the presence of a proto-solar component (δD value of ~−900‰ (ref. 42)) in the lunar mantle, in a similar way that has been used to explain Earth’s noble gas record43,44 and recent data from primitive terrestrial basalts13. If this source is indeed required to explain the extremely low H-isotopic compositions observed41 then this signature must have been added to the Moon from either material accreted from the proto-Earth or by the impactor involved in the formation of the Moon. Alternatively, such a low δD value could have arisen from contamination of a water-poor magma by solar wind-derived H present in the lunar regolith during magma ascent and emplacement.

The mantles of the early-Earth13,45 the Moon2,3,6–8 and Mars46 all seem to be characterized by water with remarkably similar H-isotopic compositions, suggesting that the same types of accreting objects as those modelled here for the Moon delivered a vast majority of the water to the rocky planets in the inner Solar System. Likewise, isotopic analyses of differentiated meteorites47 suggest that the interior of the eucrite parent body, probably the asteroid 4-Vesta, contained water characterized by H-isotopic signatures indistinguishable to that of the terrestrial planetary objects in the inner Solar System (Fig. 2).

Regarding the timing of volatile accretion to the Moon, major constraints are imposed by the time interval between lunar accretion and solidification of the LMO and overturn of mantle cumulates (~10–200 Myr after Moon formation14) since there is water in the mantle source regions of the mare basalts4,6 and picritic glasses1–3,9. It is possible that some water with Earth-like H-isotopic characteristics may have been accreted with the Moon-forming material, to explain the H-isotopic composition of water in the source regions for the picritic glasses (that were likely deep enough in the lunar mantle to have escaped processes such as degassing of H2 (ref. 48)). To account for the H-isotopic composition of the primordial lunar mantle and the urKREEP reservoir together, it is necessary that any initial lunar water was complemented by the continuous accretion of water from CC-type objects to the LMO during LAW. Incidentally, late

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Table 4 | Results from the modelling for scenario 2 considering that the water in the LMO before the late addition had undergone significant H2 degassing.

<table>
<thead>
<tr>
<th>Main CC Type</th>
<th>Max. H2O in LMO before late accretion (p.p.m.)</th>
<th>Max. % H2O added by Oort comets</th>
<th>Max. % H2O added by DEK comets</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>CM</td>
<td>9</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>CO</td>
<td>17</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>CV</td>
<td>11</td>
<td>9</td>
<td>4</td>
</tr>
</tbody>
</table>

LMO, lunar magma ocean; max., maximum.

*Assuming a BSM of ~100 p.p.m. H2O.

Table 5 | Results of modelling the amount of N in the lunar interior and the permitted proportion of cometary N added during late accretion.

<table>
<thead>
<tr>
<th>Main CC type</th>
<th>N content of 400/1,000-km-deep LMO (p.p.m.)</th>
<th>Scenario 1: max. % N from comets</th>
<th>Scenario 2: max. % N from comets initial δ15N = −2 or −40%, respectively</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>2.21</td>
<td>0.0</td>
<td>0.0, 0</td>
</tr>
<tr>
<td>CO</td>
<td>1.01</td>
<td>~5.0</td>
<td>6.8, 8</td>
</tr>
<tr>
<td>CM</td>
<td>0.95</td>
<td>0.0</td>
<td>0.25, 6.8</td>
</tr>
<tr>
<td>CV</td>
<td>1.48</td>
<td>4.5</td>
<td>6.8, ~8</td>
</tr>
</tbody>
</table>

LMO, lunar magma ocean; max., maximum. N contents based on BSM of 100 p.p.m. H2O.
accretion of material to the Earth–Moon system did not only affect their volatile inventories\textsuperscript{39} but could also explain the recently identified difference between the bulk silicate Earth and BSM in terms of W isotopes\textsuperscript{53,54}.

In summary, the lunar interior is characterized by an average bulk water content of the order of ~100 p.p.m. based on samples studies\textsuperscript{18,40} and we propose that the majority of this water was delivered during the ca. 10–200 million year-long LMO phase of lunar differentiation, with the possibility that some of this water was inherited proto-Earth-derived materials. This late accretion was dominated by water-rich carbonaceous chondrite asteroids, on the basis of H and N data, likely comprising a mixture of CO–, CI–, CM- and possibly CV-type CCs, with a minor contribution of water from deuterium-rich Oort cloud or Kuiper belt comets (much less than 20% of the total water in the BSM). Our work, therefore, confirms that the inner Solar System received a similar flux of asteroidal and cometary material for much of its early history from 4.5 billion years (this work and Dauphas et al.\textsuperscript{52}) to at least 3.9 Gyr (ref. 20) (LHB).

Methods

Mass balance calculations. For mass balance calculations, we considered a lunar radius of 1.737 4 km, a mantle density of 3.300 kg m\textsuperscript{−3}, and varied the depth of the LMO from 400 to 1,000 km. We then calculated the mass of chondritic material added to the lunar interior that would result in BSM water contents of 10, 100 and 300 p.p.m. H\textsubscript{2}O, and considered both the addition of up to 0.02% lunar mass\textsuperscript{24,25} and up to 0.4% lunar mass\textsuperscript{56}. Note that for a 400-km-deep LMO, a BSM with 10 p.p.m. H\textsubscript{2}O equates to 3.94 × 10\textsuperscript{16} kg H\textsubscript{2}O, 100 p.p.m. equals to 3.94 × 10\textsuperscript{17} kg H\textsubscript{2}O, and 300 p.p.m. equals to 1.18 × 10\textsuperscript{18} kg H\textsubscript{2}O (6.70 × 10\textsuperscript{17} kg H\textsubscript{2}O, 6.70 × 10\textsuperscript{18} kg H\textsubscript{2}O, and 2.01 × 10\textsuperscript{19} kg H\textsubscript{2}O for BSM H\textsubscript{2}O contents of 10, 100 and 300 p.p.m., respectively, for a 1,000-km-deep LMO).

Data for the average water contents of different carbonaceous, ordinary and enstatite chondrites that were used in these calculations are shown in Table 1. For carbonaceous chondrites, CI-, CM-, CV-, CO- and CR- refer to the different groups, named according to one prominent meteorite of the group, respectively Ivuna, Mighei, Vigorano, Ornans and Renazzo. OC stands for ordinary chondrites. The results of these calculations, presented in Table 2, allowed us to identify suitable impactors for the modelling presented below. For example, to add 10 p.p.m. H\textsubscript{2}O to the BSM through the accretion of enstatite chondrites alone implies the addition of >1% lunar mass for both 400- and 1,000-km-deep LMO, and, therefore, ECs were not deemed important carriers of water to the lunar interior. The same was also true for equilibrated ordinary chondrites (Table 2). Un-equilibrated ordinary chondrites were also not considered further on the basis of having prohibitively high H-isotopic compositions (Table 1) for the mixing calculations. Note that all of the scenarios in this work consider that water was efficiently delivered to the Moon regardless of if it originated in asteroids or comets, that is, we have not attempted to calculate the proportions of volatiles lost during impact into the crystallizing LMO.

Mixing models. In the mixing models, literature data for the water abundances and D/H ratios of bulk carbonaceous chondrite meteorites were utilized. Carbonaceous, ordinary and enstatite chondrite meteorites are characterized by δ\textsubscript{D} values between ~200 and +300 (refs 11,53–55). There is also a possibility that the asteroid parent bodies to the CCs may have once contained ice\textsuperscript{11}. If the asteroids that delivered water to the Moon contained ice, in addition to their bulk water contents hosted in phyllosilicates and organic matter compounds, then less amounts of chondritic material than those given in Table 2 would have been accreted to the Moon to account for the bulk inventory of water in the lunar interior. Until ice on asteroids is identified and characterized, it remains difficult to quantify how much ice, if any, could have contributed to the mixing of different H-reservoirs within the Moon. Comets 103P/Hartley 2 (ref. 56) and 45P/Honda-Mrkos-Pajdusakova\textsuperscript{27} contain water characterized by δ\textsubscript{D} values between ~200 and +400, whereas other comets studied (for example, 8P/Tuttle and 67P/Churyumov-Gerasimenko) contain water distinctly enriched in D, with δ\textsubscript{D} values >+900‰ as reported by Hartogh et al.\textsuperscript{28} in the modelling, the δ\textsubscript{D} value for water in comet 67P/Churyumov-Gerasimenko (+2,400‰ (ref. 58)) was used to represent DEK comets, the δ\textsubscript{D} value for water in Oort cloud comets was set to ~900‰ (ref. 58) for a review). For the water δ\textsubscript{D} for an asteroidal and/or cometary belt comets was given the same isotopic composition as comet 103P (+34‰ (ref. 56)).

The modelling for scenario 1 assumes no water in the lunar interior before lunar core-formation, and follows equation (1). We used the mid-range estimate for water content for the BSM of ~100 p.p.m. H\textsubscript{2}O (refs 4,9,10) (equivalent to 3.94 × 10\textsuperscript{16} kg H\textsubscript{2}O for a 400-km-deep LMO) for a review). For the water δ\textsubscript{D} for an asteroidal and/or cometary belt comets was given the same isotopic composition as comet 103P (+34‰ (ref. 56)).

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Author contributions

J.J.B. performed all calculations and modelling and prepared the first draft of the manuscript. D.A.K, J.J.B. and M.A. moulded the project. All authors were involved in the discussion of ideas and preparation of the manuscript.

Additional information

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