Endogenic water on the Moon associated with non-mare silicic volcanism: implications for hydrated lunar interior

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We have conducted spectral and spatial analysis of the Compton–Belkovich Thorium Anomaly (61.1°N, 99.5°E) region on the far side of the Moon based on high-resolution data from recent lunar missions. Chandrayaan-1 Moon Mineralogy Mapper data of Compton–Belkovich volcanic complex (CBVC) reveal the existence of a strong doublet feature near 2800 nm throughout the volcanic construct, which could be attributed to the presence of water and/or hydroxyl in the studied site. Very high resolution Lunar Reconnaissance Orbiter Camera–Narrow Angle Camera mosaic of the study area shows that the strongest of the hydration features within the CBVC is primarily related with either sunlit inner flanks of small-sized fresh craters or fresh escarpments associated with the central collapse structure. Moreover, Mini-RF Synthetic Aperture Radar data from Lunar Reconnaissance Orbiter mission suggests the presence of a thick pyroclastic deposit in the volcanic complex. Our study indicates that the enhanced hydration at CBVC could possibly have originated from the episodic events of eruption and effusion involving silicic magma, which could probably be responsible for the tapping of a zoned magma body with a water-rich cap. Morphology of CBVC also confirms the presence of episodic effusive and eruptive events that probably had led to the formation of elevated topography, central collapsed feature and late eruptive domes in the study area.

Keywords: Endogenic water, imaging spectrometer, Moon, pyroclastic deposits, silicic volcanism.

RECENT detection of OH/H$_2$O features on the Moon based on remote measurements revealed, contrary to prevailing ideas, the hydrous nature of the Moon$^1$–$^3$. Water and water-ice associated with the permanently shadowed craters of the lunar poles have also been detected remotely$^4$ and measured directly by the LCROSS impact experiment$^5$. Moreover, direct in situ measurements of lunar melt inclusions and lunar apatites indicated some parts of the deep lunar interior to be hydrated$^6$–$^8$. Here, we report the detection of strong OH/H$_2$O features near 2800–3000 nm based on Chandrayaan-1 Moon Mineralogy Mapper (M$^3$) observations over non-mare silicic Compton–Belkovich Thorium Anomaly (CBTA) region, a volcanic construct on the far side of the Moon$^9$,10. Strength of the OH/H$_2$O feature at CBTA ranges from ~6 to 17% (estimated based on convex hull continuum) relative to its surroundings having an average strength of ~3%. Based on radiative transfer models$^{11}$–$^{13}$, we have estimated a maximum OH/H$_2$O concentration of ~0.55 weight per cent (wt%) from the strongest observed 2800-nm band strength of ~17% at 30% reflectance in the Compton–Belkovich volcanic complex (CBVC).

Lunar Prospector Gamma Ray Spectrometer (LP-GRS) first identified an isolated small-scale feature with an unusually high Th abundance at Compton–Belkovich (CB) region (Figure 1) on the far side of the Moon$^9$. Jolliff et al.$^{10}$ interpreted CBTA as a compositionally evolved volcanic complex enriched in silica or alkali-feldspar indicative of rhyolitic volcanic materials based on Lunar Reconnaissance Orbiter (LRO) Diviner Lunar Radiometer and LP-GRS FeO and Th measurements. CBVC is also characterized by higher albedo than its surroundings and is associated with a positive relief feature with several volcanic cones and domes$^{10}$. High-resolution Digital Terrain Model (DTM) revealed the presence of irregular depressions within the topographic high that could probably represent collapse features associated with volcanism$^{10}$. CBVC, being an isolated KREEP-rich (or similarly

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evolved) alkaline–silicic intrusive and volcanic construct\(^\text{10}\), offers a unique opportunity to study the presence of indigenous volatiles (especially water and/or hydroxyl), if any, in the region. Here, we study the spectral characteristics of the high-reflectance feature situated at the centre of the CBVC in a spatial context to map the spectral as well as compositional diversity and detect the presence of endogenic water and/or hydroxyl, if any, associated with the late-stage silicic volcanism at CBVC based on Chandrayaan-1\(^3\) and Lunar Reconnaissance Orbiter Camera–Narrow Angle Camera (LROC-NAC) and Mini-RF observations.

New data from M\(^3\) imaging spectrometer\(^\text{14,15}\) over CBTA show diverse spectral features\(^\text{16,17}\) (Figure 2). For details on M\(^3\) data analysis and band depth estimation of 2800-nm OH/H\(_2\)O feature see Supplementary Material (online).

False colour composites (FCCs) of the study area have been generated using various M\(^3\) channels and integrated band depth (IBD) combinations to capture the first-order mineralogical variations in the study area\(^\text{16,17}\). In the FCC having band combinations of IBD-1000-nm as red, IBD-2000-nm as green and IBD-2800-nm as blue\(^\text{16}\) (Figure 3\(a\)), CBTA appears deep blue in an otherwise green to yellow background because of the enhanced hydration and lack of mafic silicates in the region compared to its surroundings. However, few green to yellow pixels have been observed within the central part of CBTA (marked by white arrow in Figure 3\(a\)) pointing possibly towards the presence of a minor mafic phase in the region.

Analysis of M\(^3\) spectra of the mafic-bearing pixels from the central part of CBTA reveals a weak 2000-nm feature (Figure 3\(a\)), having a varying band strength of ~5–7%
Figure 3. a, Integrated band depth-based FCC of CBVC (R: IBD-1000-nm, G: IBD-2000-nm and B: IBD-2800-nm). White arrow indicates green pixels at the central part of CBTA that correspond to Fe–Mg-spinel exposures. b, Normal and continuum-removed mean (average of six pixels) reflectance spectra of Fe–Mg-spinel-bearing pixels shown in (a). Black dashed lines indicate 2000-nm and 2800-nm absorption corresponding to Fe–Mg-spinel and OH/H2O features respectively. c, High-resolution LROC–NAC mosaic showing close-up of spinel-bearing lithologies within the central collapse feature associated with a ~2-km diameter crater. Maroon arrows indicate clusters of small boulders along the steeper inner flanks of the crater.

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typical of Fe–Mg-spinel, associated with a strong (average band strength ~9%) 2800-nm OH/H2O feature\textsuperscript{16} and very weak (~2%) 1000-nm mafic feature. On continuum removal, the very weak 1000-nm feature reveals two distinct and separate features centred at ~870 and 1149 nm respectively (Figure 3 b), having average band strength of ~2%, which could primarily be due to the Fe\textsuperscript{2+} charge transition in the crystal lattice of mafic silicates and/or spinel\textsuperscript{19–23}. Very high resolution LROC-NAC mosaic (spatial resolution ~2 m/pixel) of the spinel and/or mafic silicate-bearing central collapse structure reveals boulders and/or fresh rock exposures (Figure 3 c) along the sunlit inner flanks of a small, relatively young crater having a diameter of ~2 km. The boulders are associated with minor bulges/domes (Figure 3 c) that post-date the formation of the young crater within the central collapsed structure, indicating possibly a late-stage eruptive event. This is the first positive detection of a strong OH/H2O feature in association with a detectable Fe–Mg–spinel-rich lithology in an otherwise non-mare silicic volcanic complex.

The association of spinel-bearing lithology in an evolved volcanic complex having granitic (rhyolitic) composition is highly unusual and rare on the Moon. Other than CBTA\textsuperscript{16}, spinel exposures in a silicic volcanic construct\textsuperscript{24} have been only reported recently from Hansteen Alpha in the lunar near side\textsuperscript{25}. The 2000-nm spinel feature at Hansteen Alpha reportedly lacks any 1000-nm mafic and 2800-nm OH/H2O feature\textsuperscript{25}. However, we have observed minor hydrations in both Hansteen Alpha (associated with or without spinel features) and Gruithuisen Domes, silicic volcanic constructs on the near side of the Moon, having average 2800-nm band strength of ~4% (see Supplementary Material and Figures S5–S7 online).

In the southwestern edge of CBTA, a very small, young crater of ~210 m diameter (white box in Figure 1) with unusual spectral features has been observed (Figures 4 a and b). Prominent ejecta rays are seen in the high-resolution LROC-NAC mosaic (Figure 4 c). Mean spectra of the ray crater show three subdued but distinctly separate features near ~890, 1089 and 1898 nm (Figure 4 b) in association with a strong OH/H2O feature having strength of ~9% and probably represent a mixture of Type-A clinopyroxene with orthopyroxene and/or spinel. The subdued nature of the absorption features possibly represents the spectra of volcanic glass associated with a possible buried pyroclastic deposit that was excavated by...
the impact crater. Similar spectral features are seen at many places within the CBVC (red arrows in Figure 4a) and are mostly associated with fresh ejecta blankets and/or fresh escarpments described by Jolliff et al. These buried pyroclastic deposits with abundant volcanic glasses possibly host the indigenous OH/H$_2$O within the CBVC. At places, we have also observed very weak absorption features near ~1.4, 1.9 and 2.2 μm, which could be attributed to the vibrational overtones of OH and H$_2$O in the crystal lattice of hydrous mineral phases present within the central collapse feature. However, the possibility of these features being instrumental artefacts cannot be completely ignored owing to the fact that they are very weak in nature.

We have also utilized 12.6-cm (S-band) Mini-RF radar data from LRO to study the physical properties of the CBVC as the radar echo is sensitive to the presence of subsurface scatterers or interfaces, and to the surface roughness. The total backscattered power ($S_1$) image (Figure 5a) covering the central part of the study area indicates that the region is radar dark compared to the surrounding terrain. The CBVC is characterized by very low to moderate circular polarization ratio (CPR) values (average value ~0.38 ± 0.23; Figure 5b), suggesting that the area is mantled by fine-grained pyroclastic materials devoid of surface or near-surface rocks.

In order to map the extent and distribution of pyroclastic deposits within the CBVC, we have generated an m-$\chi$ decomposition image (Figure 5c) from the Mini-RF data. This method facilitates unambiguous interpretation of lunar features according to single (odd) or double (even) bounce signatures in the polarized portion of the reflections, and characterization of the randomly polarized constituents. The decomposition image indicates...
that surface scattering (blue) is the dominant scattering mechanism within the volcanic complex region (Figure 5c). Regions in blue clearly indicate a relatively thick layer of pyroclastic material that is smooth at the Mini-RF wavelength scales and has very few embedded wavelength-sized scatterers. The domes (marked with arrows in Figure 5a) appear yellowish in the decomposition image, which indicates a combination of double bounce and volumetric scattering due to their topographic relief (Figure 5c). It has also been observed that the CB region has relatively low secondary crater population compared to its surroundings (Figure 5c), which implies that it has been little modified by the impact processes, consistent with the previous results10. Decomposed image of CBTA thus helps in quantifying regions primarily dominated by surface scattering for which the CPR is ambiguous in some contexts.

At the CBVC, the strongest of the 2800-nm OH/H2O features with band strength ranging from ~9% to 17% (band strength is calculated by fitting convex hull continuum) is mostly found in association with small, young craters and their fresh ejecta blankets. Direct correlation of strong OH/H2O features with fresh ejecta blankets and sunlit inner walls of young, small-sized craters confirms that enhanced hydration at CBTA is not restricted only to the upper few millimetres of the surface, but extends significantly deeper into the lunar mega-regolith blanket and/or crust. Spectral characteristics of ejecta deposits and sunlit inner walls associated with small craters strongly suggest the presence of a possible buried pyroclastic deposit that is relatively rich in hydroxyl and/or water. Moreover, the CBVC being radar dark in the Mini-RF image indicates that the region is covered by a thick mantling material17 that supports M3 spectral observations. Fresh surfaces within the CBVC are mostly characterized by featureless spectra corresponding possibly to quartz and/or alkali-feldspar. However, weak mafic features near 1000 and 2000 nm have also been observed in the spectra of fresh ejecta deposits and fresh escarpment surfaces associated with irregular depressions, volcanic cones and domes, and/or crater walls that probably represent pyroclastic deposits having basaltic and/or noritic composition in an otherwise granitic (rhyolitic) complex. Previous studies based on LP-GRS Th and FeO data explained the composition of the CB region to be granitic (rhyolitic) or a mixture of granite and alkali anorthosite, norite and/or gabbro10, which supports our spectral observations.

The OH/H2O features near 2800 and 2900 nm, as seen in the M3 data over CBTA, clearly indicate that the regolith at the study area is primarily dominated by the hydroxyl fundamentals. However, it is not possible to completely characterize the OH/H2O feature because of the limited M3 spectral coverage (~540–3000 nm). Radiative transfer (RT) modelling11–13 of the spectra from CBTA reveals that the water concentration varies from ~0.1 to 0.55 wt% (Figure 6). We have estimated maximum water concentration of ~0.55 wt% from a spectra having ~30%
reflectance at 2800-nm and ~17% band strength of the 2800-nm feature (estimated based on convex hull continuum) (see Figure 6 and Supplementary Material online). This is also the highest estimated water concentration so far, outside the polar regions based on RT modeling of remote measurements. High-reflectance areas have band depths of ~8–9.5% corresponding to an equivalent water concentration of ~0.2–0.3 wt%, whereas the average water concentration is estimated to be ~0.3 wt%. Thus, the CBVC having unique compositional (silicic) and geological setting with high Th concentration and OH/H2O concentration should be considered as a top-priority target for future study.

The strong 2800-nm OH/H2O feature observed at the non-mare silicic CBVC could possibly indicate the presence of endogenic water associated with the late-stage silicic volcanism in the region. Direct correlation of 2800-nm hydration feature in the M3 data with that of other silicic volcanic constructs, such as the Hansteen Alpha and the Gruithuisen Domes on the lunar near side associated with evolved KREEP-rich material at Oceanus Procellarum further strengthens the possibility that endogenic water associated with silicic melts is primarily responsible for the observed enhanced hydration at CBTA. According to Jolliff et al., either extreme fractionation of a KREEP-rich magma body with upward enrichment of silicic late-stage residual melt, or large-scale gravity separation of silicic melt from a magma that reached the field of silicate–liquid immiscibility during crystallization was responsible for the formation of a non-mare silicic volcanic complex at CBTA with anomalously high Th concentration. During the late-stage near-surface fractionation of the KREEP material, OH/H2O and other volatiles being incompatible get enriched into the silicic melt. Subsequently, the volatile enriched silicic materials were brought to the surface by episodic explosive and effusive events. A progressive change from explosive to effusive style of eruption could possibly be responsible for the tapping of a zoned magma body with a water-rich cap. Morphology of CBVC also attests to the fact that the episodic effusive and eruptive events possibly had led to the formation of elevated topography, central collapsed feature and late eruptive domes.

Other possibilities include impact-induced hydration by water-bearing comet or asteroid and/or solar wind proton-induced hydroxylation. However, much stronger OH/H2O feature at CBTA having band strength of ~10–17% relative to its immediate surroundings (average band strength ~3–4%) and to the polar regions strongly suggests that endogenic water may be adding to the overall observed strength of the absorption feature. Therefore, presence of indigenous volatiles, in particular, water into the models constraining the Moon’s formation and evolution.


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Tropical grasslands supporting the endangered hispid hare (Caprolagus hispidus) population in the Bardia National Park, Nepal

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The presence of the endangered hispid hare (Caprolagus hispidus) has been confirmed in the seven grasslands (approx. 900 ha) of the Babai valley, Bardia National Park (BNP), Nepal. We conducted a presence–absence survey, studied the diet of hispid hare and evaluated vegetation composition in hispid hare habitat of the park. The pellet density was 4.07/ha before the burning season and 8.71/ha after it. The diet of the hispid hare consisted of 23 plant species, of which Saccharum spp., Imperata cylindrica, Desmostachya bipinnata and Cynodon dactylon were most preferred. These plant species were also more abundant in the hispid hare habitat. Our results showed that composition of plant species in the diet was available proportional to the hispid hare habitat. We recommend that the management authorities should prepare a species-focused management plan to conserve and monitor the hispid hare population and other small mammals of the region.

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The tropical grasslands of Nepal support a critical ecosystem and endangered wild animals, including the hispid hare (Caprolagus hispidus). The range of hispid hare is limited to the tropical grasslands of Nepal and northern India. As these grassland habitats are the main source of livelihood for local people, they are simultaneously under the pressure of fire, grazing and occasionally encroachment. Annual grass harvesting and burning are common practices adopted in the management of these tropical grasslands. However, the management especially focuses upon the charismatic large mammals and their habitats (grasslands), with less concern toward the small mammals.

Occurrence of hispid hare population has been reported in the Shuklaphanta Wildlife Reserve, Nepal. This species is possibly distributed throughout the grasslands, from the eastern to the western regions of Nepal. Yet, there is no information on the distribution of this species in other parts of Nepal. Therefore, we studied the grasslands of the Bardia National Park (BNP), Nepal. The study focused on the abundance of hispid hare based on the presence/absence information, its habitat, diet and threats faced in BNP.

The BNP lies between 80°10'E to 80°50'E and 28°15'N to 28°40'N in the western part of Nepal, extending across 968 km² as the largest national park of lowland/tropical region in the country. The park supports a large tropical biological diversity and about 3.5% of the park area is classified as grassland. The dominant grass species include Saccharum spontaneum, Imperata cylindrica and Desmostachya bipinnata. The grasslands particularly support small and large mammals, birds and other biological diversity. Seven different vegetation types have been identified, dominated by species such as Shorea robusta, Terminalia tomentosa, T. bellirica and Buchanania latifolia. BNP provides a prime habitat for endangered animal species, such as tiger (Panthera tigris), one-horned rhino (Rhinoceros unicornis) and elephant (Elephas maximus).

The study was conducted in two seasons: before the burning season (November 2008–February 2009) and after (March–June 2009) the burning season. We searched the whole grassland for hispid hare pellets in all the potential hispid hare habitats. Pellets, which are conspicuous, were identified based on earlier studies. We laid out strip transect lines (50 m × 20 m of about 1 km) systematically in each grassland and counted the hispid hare pellets. The transect lines were drawn perpendicular to the river direction in each grassland of the Babai valley and the grassland near BNP headquarters. Once we identified the plots, we marked the areas for vegetation measurement, i.e. 10 m × 10 m for the tree layer, 4 m × 4 m for shrub layer and 1 m × 1 m for grass. The plot points for each area were transformed into the digitized Topomaps of BNP, and Arc GIS 9.3 was used to prepare the hispid hare distribution map.

In total, 29 and 62 hispid hare pellets were collected from the study area before and after the burning season respectively. The samples were analysed in laboratory of Central Department of Environmental Science, Tribhuvan University, Nepal. Each sample was further analysed for microhistological diet analysis. The samples were washed with distilled water and kept for 24 h in alcohol (2%). After washing with 25% alcohol, they were oven-dried at 40°C for 24 h. Samples were further analysed as described earlier. In total, 29 and 62 slides were prepared from the samples collected before and after the fire. From each slide, 20 fragments were taken to identify the hares up to species level. The plant fragments which remained in each sample were analysed by comparing with the reference plant fragments of the area.

A total of 682 transect lines were laid out throughout the entire potential grasslands of the park. We divided the grasslands into four categories and conducted the transect survey. These included: (i) Around the park headquarters (169 transects), (ii) Lamkohili (114 transects) and adjacent areas, (iii) Lal Matti, Chisapani and Rambhapur (43 transects) and (iv) Babai valley (356 transects). Of these sites, only seven grassland patches of the Babai valley support the hispid hare population, which extends over an area of approximately 900 ha. The pellet density of the hispid hare was 4.07/ha before the burning season and 8.71/ha after it. The seven grasslands of BNP which support the hispid hare population (Figure 1) are the following.

(i) Sanosiri: This is located on the southern side of the Babai valley on the upper margin adjacent to Thulosiri grassland on the southeastern side of the Guthi post, where S. spontaneum and I. cylindrica are the dominant grass species (Figure 1).

(ii) Thulosiri: This grassland lies on the southwestern part of the Sanosiri, where S. spontaneum, I. cylindrica and Cynodon dactylon are the dominant grass species (Figure 1). Larger pellet size was recorded here than in any of the other grasslands and good coverage provided escape from predators. This grassland is similar to that of Sanosiri and was observed to be prone to poaching of other big mammals and not hispid hare.

(iii) Guthi: The Guthi grassland, in the northern part of the Babai river, lies almost in the middle of the Chepang and Parewaodar Post, where S. spontaneum and I. cylindrica are the dominant grass species. The Guthi grassland as well as Sanosiri, Thulosiri and Chittale are the preferred elephant habitats (Figure 1).

(iv) Kalinara: The Kalinara grassland lies south of the Babai river, where S. spontaneum and I. cylindrica are the main grass species (Figure 1).

(v) Ratamate: This is the only grassland supporting the hispid hare, which is not drained by the Babai river. We encountered many wild pigs during the survey periods (Figure 1).
(vi) Mulghat: This grassland lies on the west, adjacent to Machan, where the dominant grass species include *C. dactylon* and *I. cylindrical* (Figure 1). This grassland was found to be most frequently harvested by the local inhabitants from Chepang. Such activities have disturbed hispid habitat and its species, *C. dactylon*.

(vii) Nahar: This grassland lies on the western part of the Babai irrigation dam (Babai bridge on the east-west highway; Figure 1). *I. cylindrica* and *C. dactylon* are the dominant grass species. The species population was found to be the most isolated and confined among the grasslands studied, with the hispid hare population surviving under threat, i.e. flooding and the connectivity with this grassland was broken down by forest patches and rivers. Visits by the public to the Babai dam add to the threat to this grassland. No annual burning is practised here.

The diet of the hispid hare consists of 23 plant species, the 5 most preferred species are: *S. spontaneum*, *I. cylindrica*, *D. bipinnata*, *C. dactylon* and *Saccharum munja*. These constitute more than 85% of the food plant species (Figure 2).

*S. spontaneum* occurred with the highest frequency followed by *I. cylindrica* and *C. dactylon* before the burning season; *I. cylindrica* had the highest frequency followed by *S. spontaneum* and *C. dactylon* after the burning season (Figure 2). Our results showed that the composition of the plant species in the diet of the hare was available proportional to the hispid hare habitat.

This study has confirmed the presence of the hispid hare in the Babai valley. Due to the nocturnal nature of the hispid hare, we adopted the survey method, studying hispid hare pellets to understand the status and conduct a presence–absence survey. Aryal *et al.* and Yadav estimated the hispid hare population based on the pellet density in the Shuklaphanta Wildlife Reserve. We used the same method to estimate the population density from the pellet density. We found a population density of 0.452 and 0.967/ha before and after the burning seasons, with estimates that were much lower than those of the earlier studies.

*I. cylindrica*, *C. dactylon* and *S. spontaneum* were the most preferred plant species for the hispid hare to feed upon in both seasons. Similar plant species in the hispid hare diet were recorded. All the pellets were found in the grasslands dominated by *I. cylindrica* and *S. spontaneum* in the park, similar to the findings of Aryal *et al.*.
Therefore, we conclude that the hispid hare prefers *I. cylindrica*, *C. dactylon* and *S. spontaneum*-dominated grasslands, and these plant species would offer the most suitable habitat for the hare. We suggest that the presence–absence survey be conducted in other grasslands (dominated by *I. cylindrica* and *S. spontaneum* with a combination of *C. dactylon*) as well as in the Protected Areas of the tropical region (i.e. Chitwan National Park). We also suggest that the concerned authorities prepare a species-focused management plan for the conservation of the hispid hare and other small mammals of the region. At the same time a fire management strategy needs to be prescribed and implemented.


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