# The Circum-Isidis Capping Unit: An Extensive Regional Ashfall Deposit Exposed in Jezero Crater

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## Abstract

Several mineralogically diverse regions across Mars are capped by dark-toned rock formations emplaced during the Noachian-Hesperian transition, an era encompassing a shift in volcanism from dominantly explosive to effusive. However, these caprocks' origins are uncertain, limiting insight into the nature of this shift. We explore the potential volcanic ash origin of a widespread (∼50,000 km²) mafic caprock in the Circum-Isidis region via an integrated photogeologic and remote-compositional analysis. We also investigate whether this unit is genetically equivalent to a mafic rock formation exposed in the floor of Jezero Crater. We find: (a) the Jezero Floor and Capping Units are morphologically, stratigraphically, and compositionally similar, suggesting a shared formation mechanism, and (b) the tonal layering and draping characteristics of the Capping Unit are most consistent with a volcanic ash origin atop the ultramafic Olivine-Rich Unit, also an ash. Our hypotheses can be tested by the Perseverance rover and studies of returned samples.

## Plain Language Summary

In its early history, Mars volcanism transitioned from explosive to lava style eruptions. We test hypotheses for the origins of a rock formation overlying the region surrounding Perseverance rover, finding this unit is most likely a volcanic ash. We also test whether this rock unit is exposed specifically in Jezero Crater, the current location of the Perseverance rover. We find that this unit not only is equivalent to the rock formation that Perseverance landed on but also may aid in understanding the causes behind Mars' volcanic transformation ~3 billion years ago.

## 1. Introduction

Dark-toned mafic caprocks are globally distributed across Mars, such as in Nili Fossae (Mustard et al., 2009), Mawrth Vallis, Sinus Meridiani (McLennan et al., 2019), Gale crater (“Cratered Surface” in Anderson et al., 2015), and Oxia Planum, the proposed landing site for the ExoMars lander (Quantin-Nataf et al., 2021). These geologic units superpose mineralogically diverse rock formations and were emplaced during the Noachian-Hesperian transition. This period encompasses shifts in aqueous surface environments and the putative dominant style of volcanism on Mars, from explosive to effusive volcanism (Bandfield et al., 2013; Michalski & Bleacher, 2013; Robbins et al., 2011) as well as from broadly low-calcium to high-calcium pyroxene volcanic products (Baratoux et al., 2013; Mustard et al., 2005; Poulet et al., 2009). Hypotheses for the origins of these caprocks are diverse, including deposition as volcanic lava flows (Bishop et al., 2013; Bramble et al., 2017; Tornabene et al., 2008), impact melts (e.g., Mustard et al., 2009), or impact or volcanic-related air-falls (Bramble et al., 2017; Cannon et al., 2017; Edwards & Ehlmann, 2015). Resolving the formation mechanisms of these geologic units, though they may differ, would contribute to efforts to constrain the causes and nature of the Noachian-Hesperian transition, including shifts in surface environments and volcanism.

This study examines one of the most geographically widespread (~50,000 km²) and well-exposed examples of these mafic caprocks, the Capping Unit of the Circum-Isidis region (Figure 1a). It is also a potential target for sample caching by the Perseverance rover for return to Earth-based laboratories (Farley et al., 2020). The Capping Unit immediately overlies and is geographically coextensive with the Olivine-Rich Unit, which has been shown likely to be a volcanic ash deposit (Kremer et al., 2019; Mandon et al., 2020). Based on its strong coextensive relationship with the Olivine-Rich Unit as well as its apparent draping of bowl-shaped topography (Mustard et al., 2009), we explore the hypothesis that the Capping Unit may also be a volcanioclastic airfall deposit.
We also investigate whether this rock formation is equivalent to the mafic, crater-retaining Jezero Floor Unit, currently under investigation by Perseverance rover (Farley et al., 2020). Stratigraphic and morphologic commonalities between these two units have been noted (Sun & Stack, 2020). Advanced statistical and noise-reduction techniques now allow for a more rigorous comparative compositional analysis between the Jezero Floor and Capping Units. Demonstrating equivalency between these two rock formations would allow insights from the rover to be applied to the more extensive regional Capping Unit.
2. Background and Geologic Context

The Capping Unit overlies the Olivine-Rich Unit and Noachian basement (see Figure 1e)—both ancient, mineralogically diverse geologic units, with detections of Fe-Mg phyllosilicates (Bramble et al., 2017), serpentine, and carbonates (Ehlmann & Mustard, 2012). The Capping Unit is generally characterized by a dark-toned, crater-pre-
serving surface that tops mesas with steep bounding scarps (see Figure 2a). Please note that the Capping Unit of this study is geographically and geomorphically distinct from the Pitted Capping Unit of Goudge et al. (2015) (see Supporting Information S1). Spectra of the unit show weak mafic (1 and 2 μm) signatures with a mixture of olivine (Bishop et al., 2013; Bramble et al., 2017). The age of the unit is likely between 3.6 and 3.96 Ga, forming after the Isidis impact dated by Werner (2008), but before Syrtis Major lavas that are stratigraphically above it (Mustard et al., 2009).

The floor of Jezero Crater contains an olivine-carbonate geologic unit (“light-toned floor unit” in Goudge et al., 2015)) superposed by a mafic, crater-retaining floor (the “Jezero Floor Unit” of this study; “Volcanic Floor Unit” in Goudge et al., 2015)). An “Undifferentiated Smooth (Us)” unit mantles the Jezero Floor Unit (Stack et al., 2020), and recent work has determined that it likely formed after the Floor Unit (Kah et al., 2020; Stack et al., 2020; Warner et al., 2020). Recent work shows they have similar spectral signatures, indicating that the Us may be derived from the crater-retaining floor (Horgan et al., 2020; Warner et al., 2020). Thus, we follow previous studies (e.g., Goudge et al., 2015; Horgan et al., 2020; Salvatore et al., 2018; Schon et al., 2012; Shahrzad et al., 2019) and treat them as a single unit. Age estimates derived from crater-counting for the Jezero Floor Unit have ranged widely from 1.4 Ga (Schon et al., 2012) to 3.45 Ga (Goudge et al., 2015). Hypotheses for the origin of the crater-retaining Jezero Floor Unit are similar to that of the Capping Unit, including deposition as a lava flow (Goudge et al., 2015; Schon et al., 2012), cemented aeolian/fluvial sediments (Kah et al., 2020; Stack et al., 2020), or as an airfall deposit (Stack et al., 2020).

We rule out a few formation hypotheses for the Capping Unit based on previous work. An origin as an Isidis-related product/impact melt is not possible given the Capping Unit's stratigraphic position above post-Isidis features such as the Olivine-Rich Unit and Jezero Crater's rim (Kremer et al., 2019; Sun & Stack, 2020). Additionally, the Capping Unit is a coherent layer of rock that exclusively superposes and thinly drapes (with thicknesses not exceeding 10 of meters) the Noachian Basement and Olivine-Rich Units (Kremer et al., 2019; Mustard et al., 2009), precluding an origin as an igneous intrusion. Although the Capping Unit is dark-toned, mafic, and crater-retaining, these characteristics in a rock formation do not exclude a clastic origin as discussed in Edgett and Sarkar (2021). Work thus far has been ambiguous regarding whether the Capping Unit is a lava derived from Syrtis Major or vents (Bishop et al., 2013; Bramble et al., 2017; Tornabene et al., 2008), a product of impact condensates (Cannon et al., 2017), an aeolian erg deposit, or a volcanic ashfall (Bramble et al., 2017; Cannon et al., 2017; Edwards & Ehlmann, 2015). This study explores the merits of these hypotheses.

We map the extent of the Capping Unit and characterize its stratigraphic position, internal layering, draping characteristics (including relief-to-thickness ratios), and regional uniformity (morphologic, compositional). We compare our results with previous observations and the expected characteristics of ancient rocks deposited as lava flows, impact products, aeolian ergs, and ashes. We additionally compared the morphologic, stratigraphic, and compositional characteristics of the Capping and Jezero Floor Units. These analyses use data from the High-Resolution Imaging Science Experiment (HiRISE), the Context Camera (CTX), and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) aboard the Mars Reconnaissance Orbiter. Detailed spectral analyses are facilitated by endmember extraction using the statistical method Factor Analysis.

3. Methods

3.1. Mapping

To examine the regional uniformity of the Capping Unit, we conducted mapping in our study areas (14°–24°N, 76°–80°E) on the northwestern margin of Isidis and (2.5°–4°N, 82.5°–86°E) in Libya Montes at a 1:50,000 scale, using HiRISE and CTX images as well as the Murray Lab CTX mosaic (Dickson et al., 2018; Malin et al., 2007) (see Figure 1; see Supporting Information S1 for a list of images used in the study).

Mapping was guided by the Capping Unit's unique geomorphic characteristics: a dark-toned, crater preserving surface, steep bounding scarps, mesas typically 1–5 km in diameter (see Figure 2a), and its stratigraphic superposition of the Olivine-Rich Unit mapped by Kremer et al. (2019) (see morphological characteristics therein). Just as the Olivine-Rich Unit exhibits locally alternating, internal tonal layers, the Capping Unit has also been...
observed to exhibit layering at its base with alternating tonality (Bramble et al., 2017). Layering in the Capping Unit was distinguished from layering in the Olivine-Rich Unit by the presence of boulders (see Figures 2b and 2d).

### 3.2. Draping Characteristics

We explore the Capping Unit's draping characteristics: how it is oriented (i.e., dipping) with respect to underlying topography and how thinly it drapes kilometer-scale, bowl-shaped outcrops. This examination helps to differentiate between (a) deposition as an airfall (volcanic/impact) and (b) origins as a lava flow or aeolian erg. The former mechanisms would tend to drape topography thinly and with a high degree of parallelism. Although aeolian ergs and lava flows may pile against or flow over topography, thin draping (e.g., a relief-to-thickness ratio of ~10:1) across kilometer-scale, bowl-shaped topography would suggest against these mechanisms as they tend to fill, not drape low-lying depressions (Livingstone et al., 1996).

To investigate these draping characteristics, we used high-resolution Digital Elevation Models (DEMs) derived from HiRISE stereo pairs created either by the HiRISE team at the University of Arizona or in-house using the Ames Stereo Pipeline (see Table S2 of the Supporting Information S1 for Observation IDs). Outcrop orientation was measured along four stratigraphic layers: the top surface of the Capping Unit, its contact with the Olivine Rich Unit (ORU), layering within the ORU (if apparent), and the ORU's contact with the Noachian basement. It should be noted that the top surface of the Capping Unit is eroded as evidenced by impacts/pits and yardangs. Orientations of the Capping Unit outcrop surfaces (calculated from baselines on the order of 100 m) are within ~5° of horizontal (see Figure 3). The depositional mechanisms considered here (lava flow, aeolian erg, impact condensate, and ash fall) deposit materials horizontally. If the surface of the landform has remained near-horizontal, then it likely has retained its original depositional orientation. For detailed methodologies, see Text S1 in Supporting Information S1.

We additionally made topographic profiles of the Capping Unit outcrops in bowl-shaped depressions (i.e., sloping downward in all directions at the margins) to assess whether draping occurred in all directions or just from one side (e.g., downslope from a source). These measurements helped to differentiate between formation scenarios involving effusive lava and various clastic origins, the former being less likely to drape such landforms equally on all sides or with a high relief-to-thickness ratio. We also examined data from the Mars Orbiter Laser Altimeter (MOLA) aboard Mars Global Surveyor (Smith et al., 2001) to find the topographic range for the unit as a whole.

### 3.3. Spectral Signal Extraction

We assess and compare the diagnostic spectral signatures of the Capping, Olivine-Rich, and Jezero Floor Units using reflectance spectra measured by the CRISM instrument (Murchie et al., 2007) on the Mars Reconnaissance Orbiter. Similar spectral signatures between these would imply common mineralogy and lend evidence to the hypothesis of a shared origin. We use three techniques to highlight weak spectral components in the geologic units of this study: (a) endmember extraction using the HySime algorithm introduced by Bioucas-Dias and Nascimento (2008), (b) Dot-Product Mapping, and (c) Dot-Product Noise Removal.

Endmember extraction uses Factor Analysis, a statistical method that calculates eigenvectors (or “endmembers”) representative of independent variance in a data set. The first eigenvector accounts for the greatest spectral variance, while each successive eigenvector describes less. Low-order eigenvectors—those describing the most variance—tend to have spectral shapes that can be interpreted as surface/sample spectral signals and varying degrees of structured noise (e.g., Tarnas et al., 2021). While eigenvectors are useful for identifying the presence of spectral features, they should not be interpreted as exact 1:1 surface/sample signals (e.g., Tarnas et al., 2021). Endmember extraction has been applied to Mars spectral data to identify mineral components with both narrow (e.g., Amador et al., 2018; Das et al., 2022; Tarnas et al., 2019; Thomas & Bandfield, 2017) and broad absorption features (Glotch et al., 2006). Here, we use the HySime algorithm instead of the R-mode algorithm because laboratory studies have shown it to be more reliable due to HySime's separation and exclusion of noise subspaces, though non-Gaussian noise can still be present in resultant eigenvectors (Tarnas et al., 2021).
Following endmember extraction, we implemented a method called Dot Product Mapping to identify areas where each endmember is most strongly represented in the data (Das et al., 2022). This involves calculating the dot-product of an eigenvector of interest with each pixel in an Region of Interest (ROI), creating a full dot-product map. Areas that have a spectral shape corresponding to that eigenvector will have higher positive values, and those that have the inverse shape will have more negative values. This technique aids the interpretation of what may be

**Figure 3.** (a) Perspective view and interpreted cross-section of the Capping Unit draping the Olivine-Rich Unit and basement rock (DTEEC_002756_1830_002822_1830). Vertical exaggeration indicated in figure. Cross-section location indicated by the white line. The Olivine-Rich Unit and Capping Unit are indicated by green and purple arrows respectively. (b) Dip angles calculated for several Capping Unit outcrops and associated stratigraphic layers, where each line is a separate outcrop, numbered 1–7. Olv = Olivine Rich Unit. Outcrop locations are noted in Table S3 of the Supporting Information S1.
causing variation in the data, such as mineral components (e.g., spatially correlated deposits), structured noise (e.g., noisy columns), etc. Further details on these methods are given in the Text S2 in Supporting Information S1.

4. Results

4.1. Mapping and Geomorphic Measurements

We mapped 415 outcrops covering an area of approximately 5,500 km², distributed across a region spanning ∼50,000 km² and over 3 km of elevation (see Figure 1). With minor exceptions, the Capping Unit is always observed overlying the Olivine-Rich Unit. In addition to characteristic 1–5 km mesas in the Nili Planum and Libya Montes regions, we observe a more widespread (∼4,200 km²), contiguous exposure of the Capping Unit in Northern Nili Fossae (see Figure 2c). We find the Pitted Capping Unit of Goudge et al. (2015) is morphologically and geographically distinct from the Capping Unit of the present study (see Text S3 in Supporting Information S1).

Tonal layering in the base of the Capping Unit has been previously noted in Nili Planum by Bramble et al. (2017). We confirm the presence of bouldery, tonal layering across the regional extent of the unit. When apparent, this layering is parallel to sub-parallel to layering in the Olivine-Rich Unit. Figures 2c and 2d show examples of layering in the Capping Unit separated by over 20° of latitude (1,000 km) and 3,000 m of elevation. These two examples also show the layering in both the Capping and Olivine-Rich Units have similar expressions in thickness (meter-scale) and tonal variation (i.e., although the uppermost Capping Unit surface is relatively darker than the Olivine-Rich Unit, the tonality of layering in both tends to be similar; see Figure S6 in Supporting Information S1).

Topographic profiles were extracted from four Capping Unit outcrops with bowl-shaped depressions: two in Nili Fossae (Figure 3), one in Nili Planum, and one in Libya Montes (Figure S5 in Supporting Information S1). The surfaces of outcrops of the Capping Unit strongly conform to bowl-shaped concavities defined by the underlying Olivine-Rich Unit (ORU) and Basement Unit, with a relief-to-thickness ratios of roughly 10:1 (Figure 3). The Cap-ORU contact and any apparent layering in the ORU are subparallel in each case.

Dip measurements of several stratigraphic surfaces and internal bands were completed at seven outcrops (summarized in Figure 3). In each case, the one standard deviation variation of the dips was below 1.5°.

4.2. Morphological and Stratigraphic Comparisons to the Jezero Floor

The Capping and the Jezero Floor Units share several geomorphic characteristics. Circular pits and craters with raised rims are present on both units with sizes ranging from less than 10 m up to ∼100 m in diameter. Preservation in both varies from sharp-rimmed to rounded, less well-preserved rims. Cavities tend to be variably filled with aeolian sediments.

At the outcrop-scale, both units show sharp, scarp margins. Outcrops erode into lobate, sometimes sub-circular shapes with angular recesses. With further erosion, margins become scalloped and light-toned (e.g., Figures 2g and 2j).

Finally, each unit stratigraphically overlies light-toned olivine-bearing rocks with layering. Figure 2j additionally shows possible layering in the Jezero Floor Unit that is subparallel to the layering in the olivine-bearing unit beneath it. Yardangs are present in some outcrops of the Capping Unit but not the Jezero Floor Unit.

4.3. Spectroscopy

We analyzed five CRISM images acquired across the extent of the Capping Unit and one over the Jezero Floor Unit (locations are in Figure 1). We find that the third or fourth eigenvectors of the Capping and Jezero Floor Unit outcrops exhibit a pair of broad absorptions at 1 and 2 μm that in laboratory spectra are due to Fe²⁺ crystal field absorptions. These spectral properties are strongly consistent with laboratory spectra of pyroxenes. The eigenvectors from the different sites show a high degree of correspondence to each other and to laboratory spectra of high-calcium pyroxene (HCP), low-calcium pyroxene (LCP), and a Shergotty meteorite (RELAB IDs in Table S4 of the Supporting Information S1).
We also examined HySime endmember eigenvectors from Olivine-Rich Unit exposures proximal to our Capping Unit outcrops (Figure 4b). The shapes of the Capping Unit and ORU eigenvectors are similar within individual CRISM images. We discuss possible reasons for these similarities in Section 5.2.2 of the Discussion.

5. Discussion

Here we synthesize our Results and previous findings, leading us to the interpretation that (a) the Capping Unit and Jezero Floor represent a single, genetically linked unit (Section 5.1), (b) that this geographically vast rock formation exhibits characteristics most consistent with an origin as a volcanic ash (Section 5.2), and finally, (c) that this unit, combined with the Olivine-Rich Unit, may represent the products of related eruptions (Section 5.2.3).

5.1. Equivalency to Jezero Floor

In the Results section, we note morphological (Section 4.2), stratigraphic (Section 4.2), and compositional (Section 4.3) similarities between the Capping and Jezero Floor Units. We conclude that the Jezero Floor and Capping Units are genetically equivalent, and that they represent one vast geologic unit.
5.2. Origin

Here we compare observations of the Capping Unit with the expected characteristics of impact condensates, lava flows, aeolian ergs, and volcanic ash-falls.

5.2.1. Layering, Draping, and Regional Uniformity

Layering of alternating tonality in the base of the cap—which is subparallel to layering in the Olivine-Rich Unit and apparent in each far-flung region of exposure—is difficult to explain as a spherule deposit. Spherule exposures on Earth and Mars have not been observed to exhibit such tonal bands (Edwards & Christensen, 2011; Simonson & Glass, 2004), which casts doubt on an impact-product origin.

Both lava flows and aeolian ergs can create deposits which appear to drape topography. For example, an aeolian erg may pile against sloped terrain and a low-viscosity lava flow may inundate a bowl-shaped depression from all sides (particularly if originating from vents across a wide area). However, the Capping Unit thinly conforms to bowl-shaped depressions, with relief-to-thickness ratios of approximately 10:1 over kilometer-scale outcrops (see Figure 3). Thin draping to this degree suggests against deposition as an aeolian erg or lava flow, as either mechanism would tend to fill, not thinly drape such depressions (Livingstone et al., 1996). The Capping Unit does not appear to flow along topographic lows, as would be expected from a lava flow. Furthermore, the remarkably uniform morphology and layering of Capping Unit outcrops separated by 1000s of kilometers and 1000s of meters of elevation (see Figures 2c and 2d) casts doubt on an aeolian erg hypothesis.

An ash-fall origin is consistent with the Capping Unit’s exceptionally thin draping of bowl-shaped topography, regional uniformity, as well as its meter-scale bands of alternating tonality (e.g., Houghton & Carey, 2015).

5.2.2. Association With Olivine-Rich Unit

An ash-fall hypothesis is further supported by the Capping Unit’s strong stratigraphic and geomorphic similarities with the Olivine-Rich Unit, shown by Kremer et al. (2019) and Mandon et al. (2020) to most likely be a volcanic ash deposit. Across 50,000 km², the Capping Unit is virtually always observed overlying the Olivine-Rich Unit (Figures 1b and 1c). Their contact and internal layers are parallel (Figure 3b). Tonal layering within both units are similar in both vertical scale and tonality (Figure 2e). The Capping Unit thinly and conformably drapes topography (Section 3.2), very similar to the behavior of the Olivine-Rich Unit (Kremer et al., 2019). Within Jezero Crater, Kah et al. (2020) note tonal and textural similarities between the Jezero Floor Unit and the Olivine-Rich Unit beneath it.

Beyond these stratigraphic and geomorphic associations, we can also compare the composition of these two units. Figure 4b shows the similarities in crystal-field absorptions between the Olivine-Rich and Capping Units. We interpret that this is a pyroxene signal tied to bedrock composition, not the composition of weathered sediments, because the eigenvector Dot-Product Map of the pyroxene signal is distributed uniformly across both units instead of being concentrated in topographic lows (e.g., craters, pits) or at the edges of scarps.

The conformable contact between both rock formations across such a wide region is notable given the Olivine-Rich Unit’s high friability (Kremer et al., 2019). This, in tadem with observations of strikingly similar layering structures, draping behavior, and compositional associations all point to a shared formation mechanism as an air-fall deposit from a volcanic source.

5.2.3. The Olivine-Rich and Capping Units: A Shared Source?

The many similarities between the Olivine-Rich and Capping Units further prompts consideration of the following possibility: that these two geologic units may represent the products of related eruptions. Possible causes for the ultramafic to mafic geochemistry observed include a pre-depositional geochemical shift in magmatic source(s) or post-depositional alteration by aqueous processes (Kaufman et al., 2022). If the former, analyses of melt inclusions in sample olivine crystals would potentially lend insight into a chemically evolving magmatic system on Mars. If the latter, in-situ and lab analyses would help determine the timing and nature of aqueous activity at Jezero Crater (Kaufman et al., 2022).

The precise location of a source for this extensive amount of volcaniclastic material remains unclear. Source vents could have been overlain by Syrtis Major lavas or eroded away in the significant time since emplacement.
As yet unidentified, highly eroded sources may exist as have been found in other regions of Mars (Michalski & Bleacher, 2013).

5.3. Validation

Our remote-sensing investigation prompts hypotheses that in-situ analysis by Perseverance rover can test. Origin (e.g., deposition as volcaniclastic or lacustrine epiclastic) may be assessed by examining the unit's grain morphology and whether the unit exhibits planar versus cross-bedded features. For example, Ruff et al. (2014) demonstrated an air-fall origin for the olivine-rich rocks in Columbia Hills by examining the unit's highly angular grain morphology. Equivalency of the Capping Unit and Jezero Floor may be tested through bulk chemical analyses and a more detailed inspection of morphology. The hypothesis that the Olivine-Rich and Capping Units are products of related eruptions may be similarly substantiated by further in-depth morphological and compositional analyses.

5.4. Implications

5.4.1. Timing of Aqueous Activity at Jezero

A volcanic ash-fall origin for the Jezero Floor, as opposed to a cemented lacustrine/erg origin, would allow future Earth-based laboratory analysis to determine the timing of the unit's deposition. This would provide a critical upper bound on the age of Jezero's aqueous activity.

Should the Jezero Floor and olivine-bearing unit beneath it prove to be a sequence of ashes, this would support the hypothesis that the Delta Unit lies at least mostly above instead of between the Olivine-Rich and Jezero Floor Units.

5.4.2. Mars' Volcanic Transition 3 Ga

Given the Capping Unit's age of 3.6–3.96 Ga (Mustard et al., 2009; Werner et al., 2008) it was likely emplaced during a global shift in Mars volcanism in the late Noachian/early Hesperian: from explosive to effusive volcanism (Bandfield et al., 2013; Robbins et al., 2011) as well as from broadly low-calcium to high-calcium pyroxene volcanic products (Baratoux et al., 2013; Mustard et al., 2005; Poulet et al., 2009). The timing and underlying causes of this volcanic transition are uncertain. However, analysis of melt inclusions within returned samples from the Capping and Jezero Floor Units could help resolve competing causal hypotheses in the literature for this shift, such as volatile depletion (Bandfield et al., 2013) versus cooling of the mantle (Baratoux et al., 2013).

6. Conclusions

We mapped and analyzed the Circum-Isidis Capping Unit's stratigraphic position, internal layering, draping characteristics, and regional uniformity. Comparing to the expected characteristics of several proposed formation mechanisms, we find its expression is most consistent with deposition as a volcanic ash. Geomorphic and compositional similarities with the Jezero Floor Unit imply that the two units are related, either in terms of a formation mechanism, or even the same formation event/sequence.

We note many similarities between the Capping Unit and Olivine-Rich Unit, including their stratigraphic correlation, similar internal layering morphologies (tonality alternations, vertical scale), parallel contacts and internal layers, and a conformable contact across 50,000 km², despite the notably friable nature of the Olivine-Rich Unit (Kremer et al., 2019). This prompts consideration of the possibility that these two rock formations represent the products of related eruptions. The ultramafic to mafic chemistry of this possible “sequence” could have been caused by either pre- or post-depositional processes (e.g., a chemically evolving magmatic source or differences in exposure to aqueous alteration as suggested by Kaufman et al., 2022). Future detailed morphologic and compositional analyses by Perseverance rover may be able to provide further insight into these possibilities.

This sequence of ash layers, which would likely include fluid and melt inclusions within the olivine grains, would have tremendous petrologic value for understanding the magmatic processes that occurred during the unit's formation concurrent with the Noachian/Hesperian transition. This makes it an important target for in-situ exploration and sampling by the Perseverance rover.
The origins and petrogenetic relationships of dark-toned caprocks in several other mineralogically diverse regions on Mars are uncertain and remain as an area of future work. Regional analyses of integrated photogeologic and compositional datasets are required to ascertain the origins of those rocks, and comparative studies are required to understand their relationships to each other. Though their origins likely differ, understanding their formation histories would contribute to efforts to constrain the causes and nature of the Noachian-Hesperian transition, including transformations in surface environments and volcanism.

Data Availability Statement

Laboratory spectra included here may be acquired from the NASA/Keck Reflectance Experiment Laboratory (RELAB) at Brown University (https://pds-speclib.rsl.wustl.edu/search.aspx). HiRISE images may be downloaded from the mission’s website (https://hirise-pds.lpl.arizona.edu/PDS/). The CTX image mosaics can be found at the Murray Lab at Caltech (http://murray-lab.caltech.edu/CTX/tiles/beta01/). CRISM images and the MOLA map are available from the Planetary Data System Geosciences Node (https://pds-geosciences.wustl.edu/missions/mro/crism.html and https://pds-geosciences.wustl.edu/missions/mgs/mola.html, respectively). Some of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (80NM0018D0004). The data used in this paper are available at https://zenodo.org/record/6354669#.YjHoLhrMKU.

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