Steep-fronted ice-rich deposits in the Alba Mons region (Mars): Morphology, distribution, and potential terrestrial analogues.

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Introduction:

Assessing the nature and distribution of water ice in the mid-latitudes of Mars is fundamental for the understanding of the planet's recent climate history [1], and for characterizing ice reservoirs as a resource for future human exploration [2].

Impact craters are ideal locations to search for ice-rich deposits as their pole-facing slopes act as cold-traps, favoring the deposition and preservation of the ice [3, 4]. Numerous works have already identified ice-rich deposits in mid-latitude craters, such as Levy *et al.* [5] with a global map of concentric crater fill (CCF), or other studies on small-scale viscous flow features (VFF) in craters, such as small glacier-like forms (GLF) [6, 7] and lobate debris aprons (LDA) [8]. More recently, Sinha & Vijayan [9] reported lobate ice-rich deposits on pole-facing crater slopes in the Alba Mons region and dated them to between 10 and 100 Ma. Also, Schiff et al. [10] studied the texture of similar deposits on the slopes of the Alba Mons caldera and observed an ice-rich mantle superimposing these deposits, interpreted as younger and showing a "hummocky" texture with few superimposed craters.

In most craters around Alba Mons, at least two distinct generations of deposits can be observed: lobate ice-rich features as "lower deposits" (LD), and a superimposed, hummocky textured, "upper deposit" (UD) interpreted as an ice-rich mantle. Figure 1 shows two examples of craters with distinct LD morphologies. This presentation focuses on a specific type of LD, illustrated in Figure 1A: tongue-shaped lower deposits with a steep front. We analyze their spatial distribution, morphological characteristics, and possible terrestrial analogues—particularly Icelandic debris-covered glaciers. This work is part of a larger project where our goal is to constrain the relative chronology of all these ice-rich units and to infer the climatic conditions responsible for their formation and preservation.

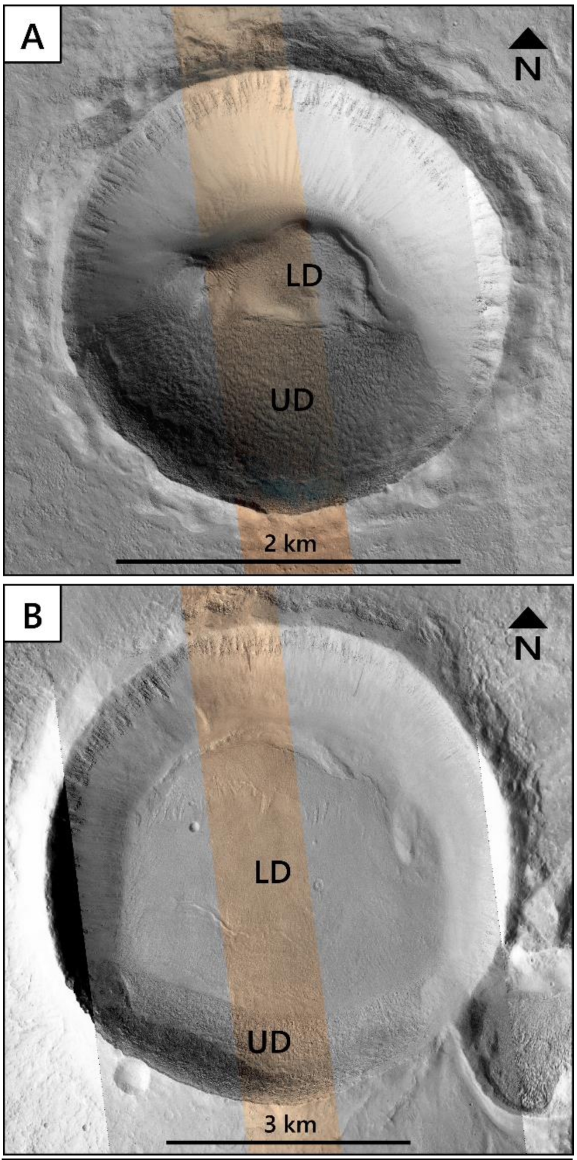

Figure 1 – HiRISE observations showing craters with upper deposits (UD) superimposed on two different forms of lower deposits (LD). **A** – Crater hosting a LD with a steep front. ESP_085484_2220. **B** – Crater hosting a LD with no steep front. ESP_086709_2170.

Dataset and approach:

Both upper deposits and lower deposits were mapped using the ~5 m/pix MurrayLab CTX mosaic [11] in the Alba Mons region, from 27° to 62°N and 79° to 142°W. We selected craters larger than 2 km that have sufficient data quality to investigate the surface texture in the database of Robbins and Hynek [12]. For each of the 1955 craters, we examined surface textures to identify the hummocky appearance of upper deposits (UD) and to detect tongue-shaped lower deposits (LD) with a steep front.

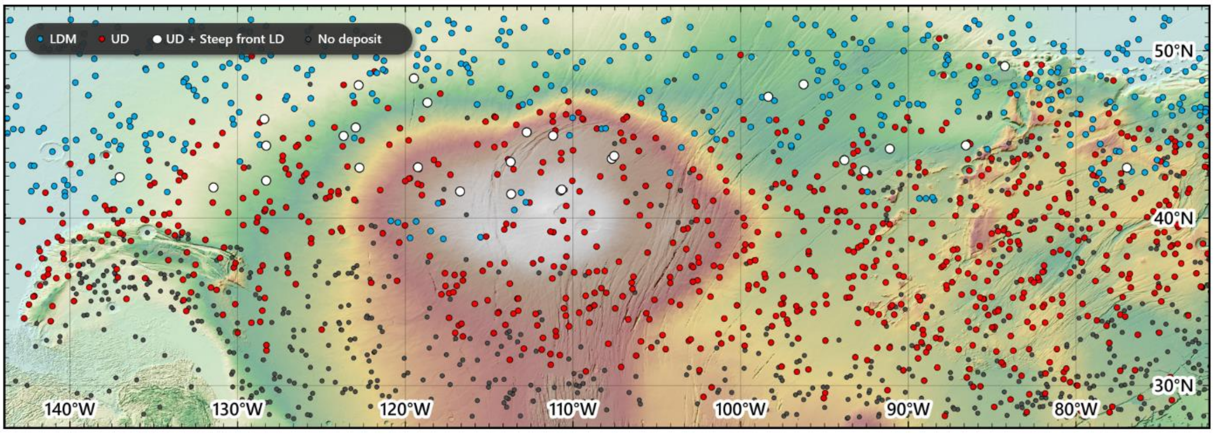

Figure 2 – Global map of all the craters larger than 2 km in the study area. Blue points correspond to craters covered by the LDM, red points to craters hosting upper deposits (UD), white points to craters hosting UD superimposed on a tongue-shaped steep front lower deposit (LD) -which are the focus of this presentation-, and grey points to craters with no deposits.

Based on our observations, we classified the craters into four categories:

- Craters without any deposits (no LD or UD)
- Craters with UD (with or without a LD)
- Craters with both UD and a steep-front, tongue-shaped LD
- Craters filled or obscured by younger units, mostly the latitude-dependent mantle [13] at higher latitudes.

In this study, we focus exclusively on craters hosting tongue-shaped lower deposits with a steep front. We investigated their morphology using newly acquired images from the High-Resolution Imaging Science Experiment (HiRISE) at 25-50 cm/pix and the Colour and Stereo Surface Imaging System (CaSSIS) at 4.5 m/pix. Where available, stereo pairs from HiRISE and CaSSIS were used to generate Digital Terrain Models (DTMs) with a resolution of 1–2 m/pixel and 15–20 m/pixel, respectively. These DTMs allow us to investigate the three-dimensional geometry of the LDs and to estimate their volume, potential dynamics, and internal structure.

Results:

Distribution of LDs with steep fronts: Within the study area, 837 craters contain at least an upper deposit (UD), but only 29 of them have a tongue-shaped lower deposit (LD) with a steep front. Figure 2 shows the spatial distribution of craters hosting various types of deposits. LDs with steep fronts (white dots) are mostly located north of 40°N, concentrated in the northernmost craters of the study area. Their poleward extent appears limited by the presence of the younger latitude-dependent mantle (LDM), which covers the entire surface topography and obscures older deposits. When extending the survey beyond the longitudinal bounds of the study area shown in Figure 2, no additional craters with LDs of this type were found, suggesting a regional specificity of these features.

By comparing the distribution of LDs with steep fronts with a map of modelled water-ice accumulation at 35° obliquity [1], we observe that these LDs are located near the edge of the modelled seasonal ice mantle, and do not correspond to zones of net accumulation. However, simulations with lower obliquities or

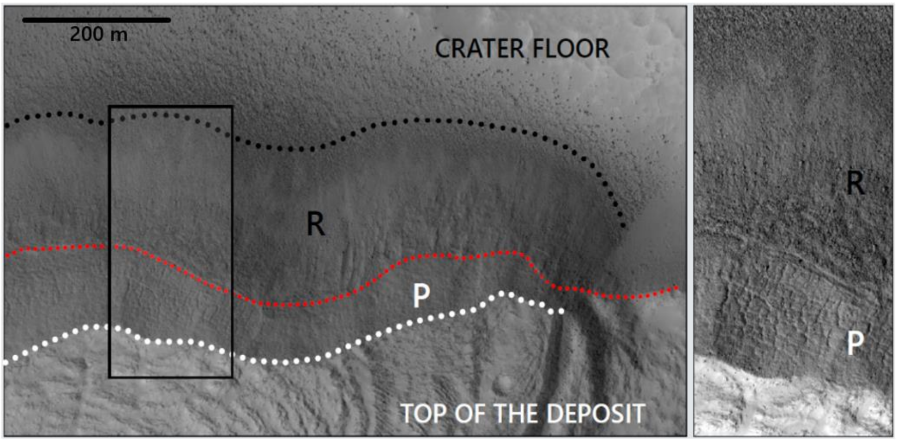

Figure 3 – Example of one of the LD steep fronts. The top of the deposit is at the bottom of the figure, and the crater floor at the top. The white dotted line indicates the top of the scarp, cross-cutting the surface features. The black dotted line indicates the bottom of the scarp. The red dotted line shows the limit between the polygonised upper layer and the rougher lower layer scattered with boulders.

higher dust content [14] show a closer match, suggesting that LD formation may be associated with alternative climate configurations. Further investigation is required to better constrain the climatic conditions favouring their development, particularly considering hillslope orientation and steepness.

Morphology of the steep fronts: The steep termination of 29 identified lower deposits offer insights into their internal structure and thickness. Using HiRISE DTMs, we find that deposit thickness at the front ranges from ~120 m to over 250 m for the largest examples—remarkably thick given their limited lateral extent (only a few kilometres long), pointing to localized substantial ice accumulation.

On Figure 3, we show a representative example of one of the steep fronts. The quantity of boulders and the way the terminal scarp cuts the ridges at the surface of the deposit (white dotted line on the figure) seems to indicate that the front is retreating as the ice within it sublimes. On the scarp, we observe two layers with distinct textures. The upper one is polygonised (P) while the lower one is rougher and covered by talus cones (R). These two layers are separated by a thin slightly protruding bed (red dotted line on the figure). These could indicate either a deposition chronology with at least two events forming the LD, or complex post-deposition dynamics of the deposit leading to the formation of two internal layers with different characteristics.

Potential terrestrial analogues:

Because the processes leading to the formation of thick, steep-fronted LDs with two distinct layers remains poorly understood, we explored potential terrestrial analogues to gain insight into their dynamics. Our goal was to identify landforms on Earth with similar morphology, and to examine their context and behavior. In particular, we searched for debris-covered glaciers and/or rock glaciers that display steep frontal scarps exposing two contrasting textural layers.

We have identified a few examples of rock glaciers with layered fronts [15], such as the one shown in Figure 4 and described in [16]. For this Argentinian case, the two layers are clearly visible, but their textures do not closely resemble those observed on Mars. The smooth unit lies in the lower part of the scarp, while the upper layer appears more rocky—opposite to what we observe on martian LDs, where the upper unit is polygonised and the lower one rough and covered with boulders (Figure 3).

Moreover, the surface of terrestrial rock glaciers typically has numerous ridges and folds indicative changes in flow speeds in reaction to various environmental factors [16]. In contrast, Martian LDs display only limited surface features, with a relatively smooth and polygonised surface, suggesting differences in formation processes, material properties, or preservation conditions.

In contrast, the overall surface morphology of Martian LDs—when not covered by an upper deposit (UD)—appears more consistent with that of debris-covered glaciers. We identify a few terrestrial examples of debris covered glaciers with steep fronts which expose two layers of differing textures, although the layers are not as easy to identify compared to the rock glaciers discussed above.

Grænavatnsjökull, shown in Figure 5, is one of these examples, and we plan to investigate it in the field. Aerial and remote sensing imagery suggest that its front may expose two distinct layers. Our goal is to determine whether these layers differ in composition, texture, or other properties, in order to constrain their origin and assess whether similar processes could explain the layering observed in Martian LDs.

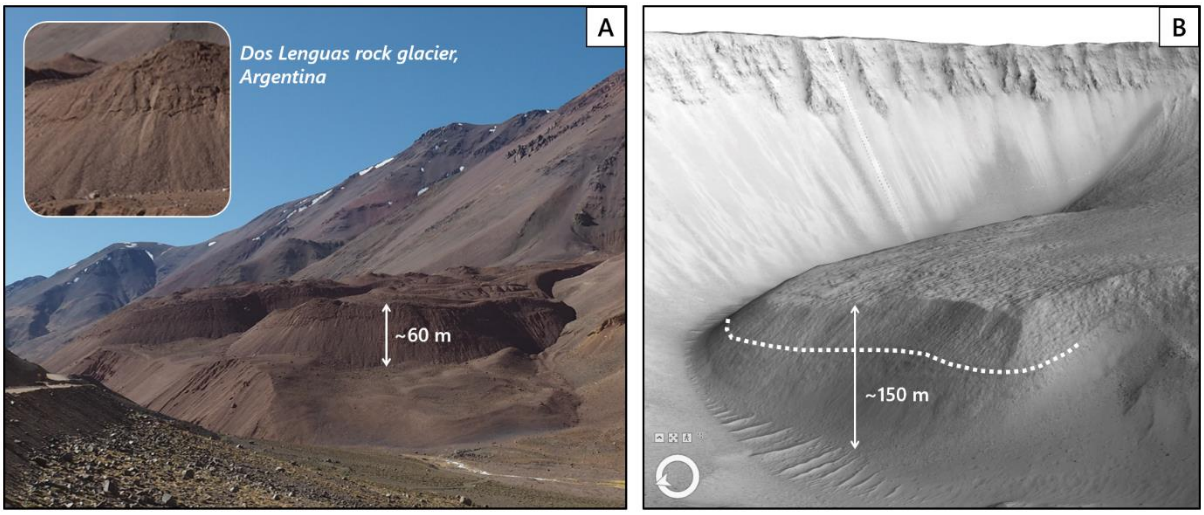

Figure 4 – Comparison between the steep front of a rock-glacier in Argentina on Earth **(A)**, and of a martian tongue-shaped pole-facing lower deposit (LD) in one of the craters of the study area **(B)**. The photography on panel **A** was taken by Costanza Morino in 2023. The 3D view with no vertical exaggeration on panel **B** was created using HiRISE high-resolution DTM and orthoimages (ESP_085497_2225 and ESP_085629_2225).

Conclusion:

Our mapping reveals that steep-fronted, tongue-shaped lower deposits (LDs) in the Alba Mons region are rare, spatially restricted, and show distinct morphological and structural characteristics. Their internal layering and considerable thickness—up to 250 m for deposits only a few kilometers long—suggest substantial ice accumulation, potentially shaped by climatic conditions not yet fully constrained. Moreover, their sharply defined frontal scarps and the presence of well-developed polygons—both on the upper part of the scarp and on the surface of the deposit—suggest that these landforms are not only thick, but also potentially very ice-rich and relatively recent.

While terrestrial analogues such as rock glaciers and debris-covered glaciers offer useful comparison points, none fully reproduces the Martian morphologies. Field investigations, particularly at Grænavatnsjökull, could help refine our understanding of the processes involved and better assess the relevance of these analogues for interpreting these martian ice-rich landforms. Our analysis of the stratigraphy, properties, and dynamics of ice-rich deposits observed in Martian craters is expected to provide additional constraints for climate model simulations, and to improve our understanding of the extent, accumulated and preserved ice, and timing of recent glaciations on Mars.

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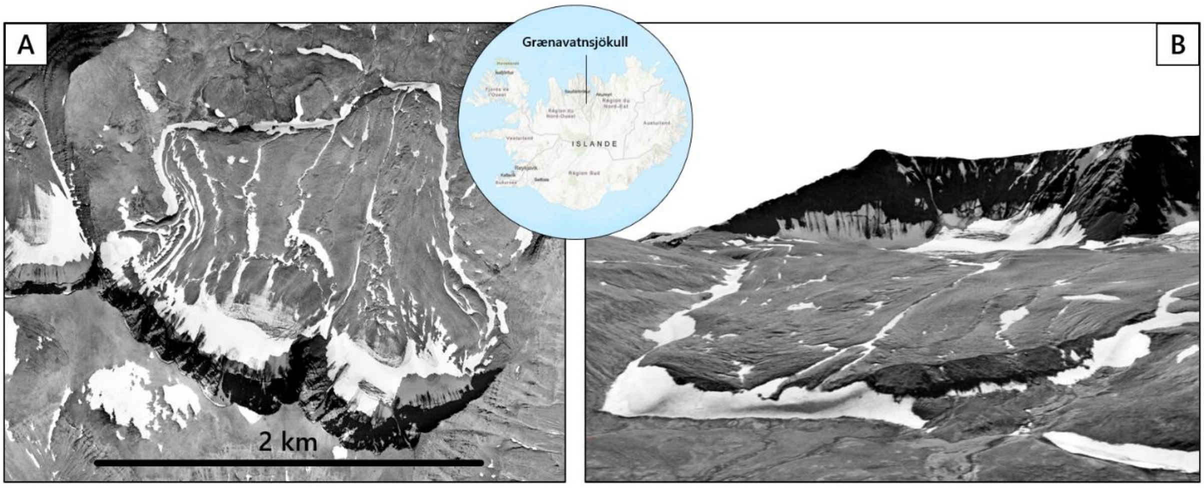

Figure 5 – Aerial image (**A**) and 3D reconstruction with no vertical exaggeration (**B**) of Grænavatnsjökull rock-glacier in Iceland. Two layers are distinguishable on the front in the reconstructed 3D view. The upper layer occupies most of the front and appear less steep than the underlying one, that is barely visible in the shadow and partially covered by snow. Elevation data and orthoimages are from the ÍslandsDEM made available online by the Natural Science Institute of Iceland [17].