Crater-Associated Irregular Cellular Structures on Mars: A New marker for the detection and the study of Debris-Covered Glaciers.

L. Scordia, S. J. Conway, *Nantes Université, Univ Angers, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, 44000 Nantes, France*, **A. Johnsson,** *Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden*.

Introduction

Mars, currently a cold and hyper-arid global desert [1], hosts significant water ice sequestered in three primary reservoirs: (1) the polar caps [2, 3], (2) ground ice – also called the latitude dependent mantle [4, 5] and (3) ice-rich deposits collectively termed 'Viscous Flow Features' – interpreted as debris-covered glaciers [6, 7, 8]. Debris-covered glaciers are prevalent in Mars' mid-latitudes ($30°$-$60°$) and are estimated to represent a total ice volume of $\simeq 4.2 \times 10^5$ km^3 [9, 10] – approximately twice the total volume of glaciers on Earth. The debris cover means their ice content cannot be estimated directly [11, 12], and instead it is inferred from geomorphic (e.g., observation of flow features [13]) and geophysical (e.g., radar measurements [14]) evidence. However, both of these identification methods have limitations, leading to a likely underestimation of the volume of debris-covered glaciers. These limitations highlight the need for new, widely applicable measurements to improve our estimates of water ice at Mars' mid-latitudes. These would provide better constraints for Global Climate Models, enhancing our understanding of Mars' past climate, while also informing the spatial distribution of water ice available for future human exploration via In-Situ Resource Utilization (ISRU).

Previous studies concerning glacial environments on Mars have reported an irregular cellular landform at the surface of debris-covered glaciers and called it different names[15, 16, 17, 18, 19]. Their size of hundreds of meters allows these landforms to be observed and identified with images such as NASA's CTX data, covering the entire Martian mid-latitudes [20]. However, these landforms have never been systematically documented, which prompted us to do a preliminary survey to constrain their distribution. We identified them throughout the northern mid-latitudes and observed them systematically within the ejecta extent of impact craters (see Fig. 1). This observation led us to name these landforms Crater-Associated Irregular Cellular Structures (CAICS) and to hypothesise that CAICS form by the interaction between impact crater ejecta and the debris-covered glacier surface. We also observed that some of the CAICS identified were on the surface of unmapped VFF. Our study therefore aims to describe the morphology of these landforms, to map their spatial distribution through the northern mid-latitudes and to confirm their relationship with impact crater ejecta.

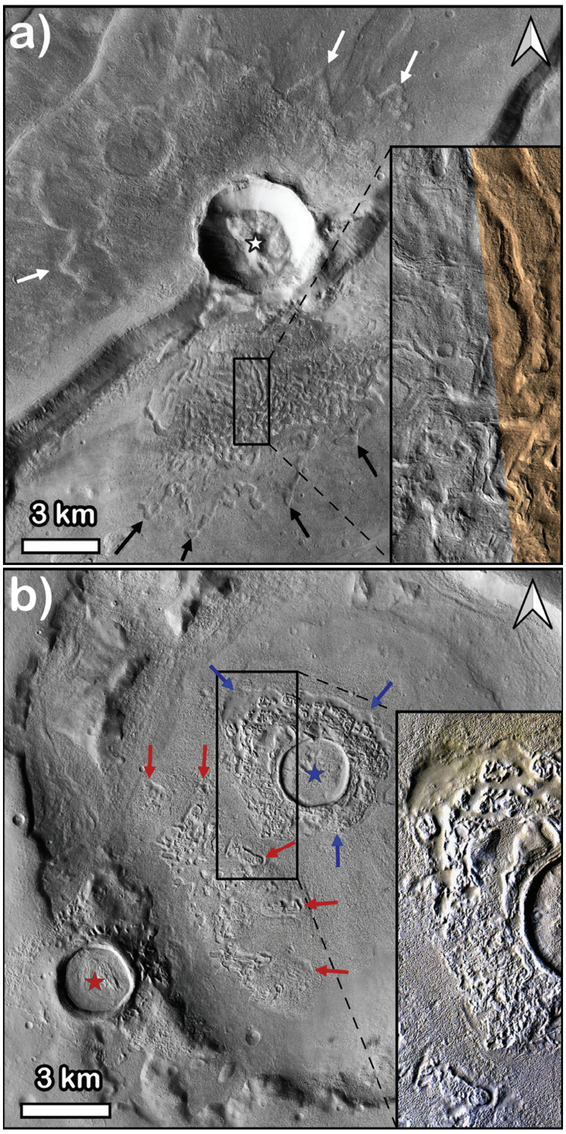

Figure 1: a) Impact crater (white star, 40.05°N -75.76°E) with its northern lobate ejecta (white arrows) and a CAICS complex to the south, which also has lobate boundaries (black arrows) (close-up view HiRISE ESP_046672_2205 RGB). b) 20 km-diameter impact crater (36.18°N 50.67°E) filled by a debris-covered glacier [10], with two superimposed craters (red and blue stars) and their associated CAICS complexes (close-up view CaSSIS image MY37_024764_145_0 RPB).

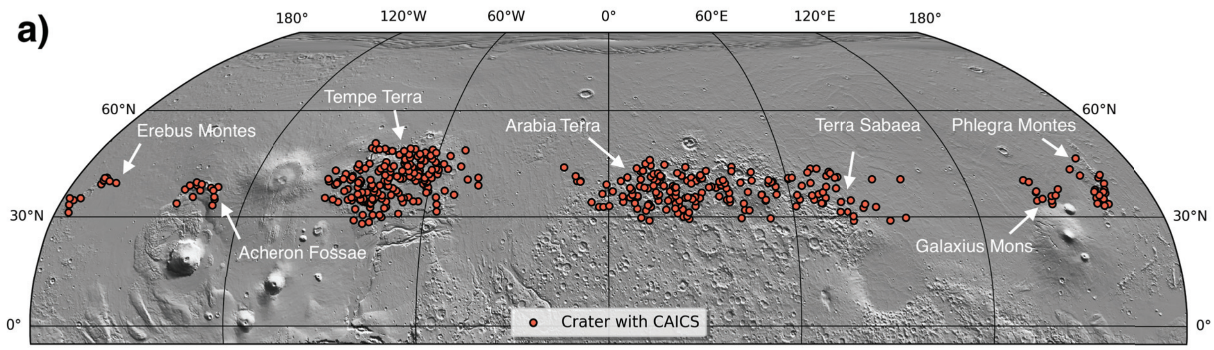

Figure 2: Distribution map of craters with CAICS throughout the northern hemisphere.

Data & Methods

To identify and study CAICS throughout mid-latitudes, we used imagery data from NASA's Context Camera (CTX) aboard the Mars Reconnaissance Orbiter (MRO) via the MurrayLab CTX mosaic [20]. For morphological and textural characterization, we used data from NASA's High-Resolution Imaging Science Experiment (HiRISE) [21, 22], offering 0.25-0.50 m/pixel resolution and ESA's Color and Stereo Surface Imaging System (CaSSIS) aboard the ExoMars Trace Gas Orbiter with $\simeq 4$ m/pixel images across four spectral bands (NIR, RED, PAN, BLU) [23]. Digital Elevation Models (DEMs) were generated from stereo pairs of CTX and HiRISE images using the MarsSI online tool [24] and USGS/BAE Systems SOCET SET processing [25]. Contextual data included published maps of VFF [9, 10].

For each CAICS we identified the most likely source impact crater as judged by its proximity and, more importantly, the relative stratigraphy between the CAICS and its and other craters ejecta fields. For instance, a crater is excluded as a candidate source if its ejecta underlie the crater hosting the debris-covered glacier with CAICS on its surface, necessitating that the candidate crater be younger than the host crater where the CAICS are observed. Identified craters may exhibit multiple distinct CAICS complexes nearby.

Results

The survey identified over 400 craters with CAICS between $28°$N and $56°$N, clustering in regions such as heavily cratered highlands and regions with a complex topography (see Fig. 2). CAICS have been identified at the surface of every type of VFF (i.e., Lobate Debris Aprons, Lineated Valley Fills, Crater Fills and Glacier-Like Forms) and are associated with a wide range of crater diameters (from 0.7 to over than 30 km). A comparison analysis with the Winslow crater ($3.73°$S $59.15°$E) shows ejecta with irregular cellular shapes, increasingly separated with distance from the crater. The similarities in shape, size and spatial distribution be-

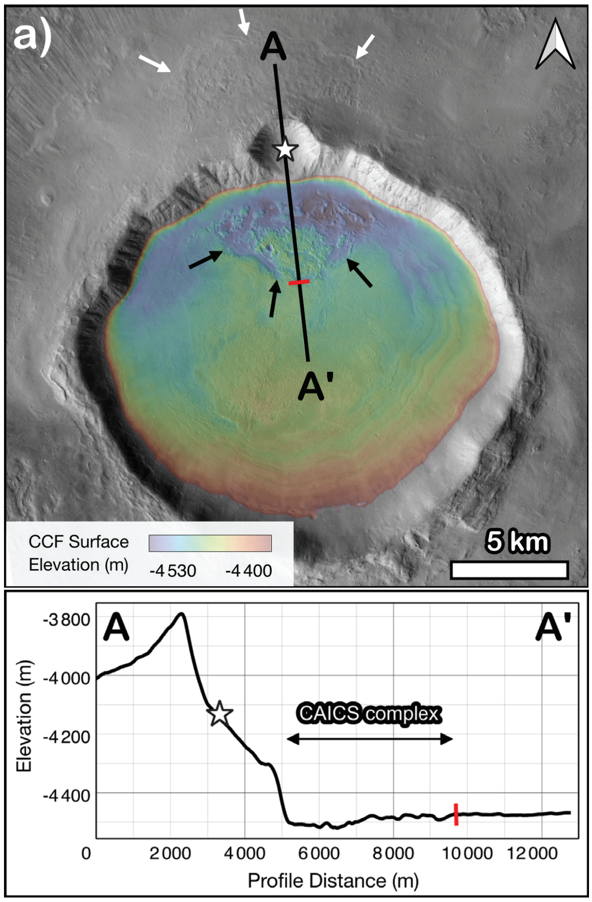

Figure 3: CTX image with a CTX DEM clipped to the extent of the debris-covered glacier. A superimposed crater (white star, where white arrows mark the ejecta extent) – on the rim of the larger crater ($39.98°$N $139.75°$E) – is the source of the CAICS complex located to the south (black arrows).

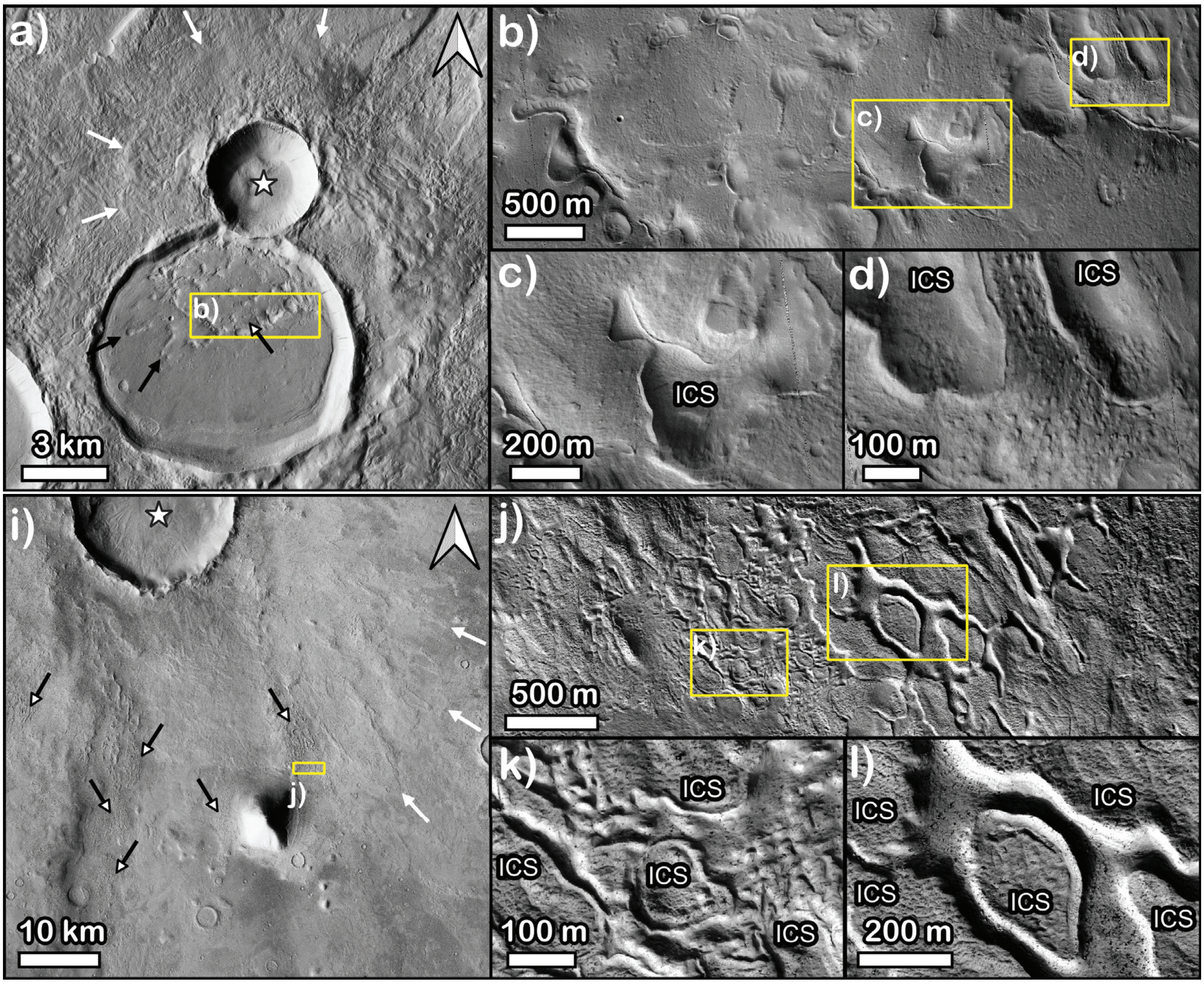

Figure 4: a), i) CTX images of two craters (06-1-003436 and 14-1-000190 from [26] respectively) with their ejecta extents marked by white arrows, associated with one or several CAICS complexes (white-head black arrows). Black arrows in a) show the lobate boundaries of the CAICS complex. b), j) HiRISE images (ESP_056628_2150 and ESP_048008_2215 respectively). c-d), k-l) Close-up views of b) and j). Yellow boxes indicate panel locations (b-d, j-l). Light source from the left. ICS=Irregular Cellular Structures.

tween the Winslow crater ejecta and our observations of CAICS support our hypothesis that ejecta are the key component initiating the formation of CAICS.

A spatial relationship analysis between CAICS and their associated crater showed that over 58% of craters have CAICS complexes only partially within their ejecta extent, also extending beyond. We observed a relationship between the CAICS extent, the local topography, and the extent of debris-covered glacier surfaces. We propose that the topography, and thus elevation differences around the impact site, influences the distance traveled by ejecta, either reducing or increasing their extent. In parallel, we also suggest a modification in the sliding behavior of ejecta on a debris-covered glacier, where enhanced sliding may occur due to the icy, lubricated surface [27]. This process could enable ejecta to form CAICS on the debris-covered glacier at distances greater than the ejecta extent observed on ice-free terrains.

Our detailed morphological analysis revealed different CAICS morphologies (Fig. 4), including bowl-shaped Irregular Cellular Structures (ICS), with varying levels of infill, and diverse Interstitial Zone (IZ) textures such as brain terrain and smooth trenches. These findings lay the groundwork for understanding the different structures within CAICS complexes and how they might evolve over time. DEM analyses from CTX and HiRISE data revealed elevation differences at scales of meters to tens of meters for ICS and trench depths, ranging from 5 to 30 meters, highlighting CAICS are mostly concave in shape. The topographic profiles also confirmed CAICS are superficial landforms on debris- covered glacier surfaces (see Fig. 3).

We hypothesize that CAICS form through subsidence of debris-covered glacier surfaces under the weight of impact ejecta, coupled with increased ice density due to heat diffusion from the ejecta, which creates bowl-shaped irregular cellular structures (see Fig. 4b-d). A better understanding of these mechanisms should be obtained with numerical modeling. Then, these primary hollows could then undergo filling. The interstitial zones, which show brain terrain and trenches, likely result from sublimation-degradation of glaciers, where irregular cellular structures are protected by the debris-ejecta cover. The combination of these filling and degradation processes should lead to the morphology observable in the Figures 4j-l).

Conclusion and Future Work

This study has demonstrated that Crater-Associated Irregular Cellular Structures (CAICS) serve as a reliable new indicator for detecting and studying debris-covered glaciers on Mars. Our observations show a strong spatial correlation with impact craters and a similar pattern of CAICS to impact ejecta, which support a key role of ejecta in their formation.
Future research should leverage CAICS for practical applications: (1) detecting debris-covered glaciers even in the absence of visible surface flow features, expanding ice inventory estimates; (2) serving as stratigraphic markers to date glacial deposits via Crater Size-Frequency Distribution (CSFD) analyses on crater ejecta, which are less prone to degradation than debris-covered glacier surfaces; and (3) informing broader studies on Mars' past climate through glacial dynamics and depositional periods. These efforts will enhance our understanding of the Amazonian climate and identify ice resources for human exploration, positioning CAICS as a key tool for advancing Martian cryosphere research.

References

[1] V.R. Baker. Nature, 412(6843):228-236, 2001. doi: 10.1038/35084172. [2] Jeffrey J. Plaut. Science, 316(5821):92-95, April 2007. doi: 10.1126/science.1139672. [3] Nathaniel E. Putzig. Icarus, 204(2):443-457, December 2009. doi: 10.1016/j.icarus.2009.07.034. [4] John F. Mustard. Nature, 412(6845): 411-414, July 2001. doi: 10.1038/35086515. [5] James W. Head. Nature, 426(6968):797-802, December 2003. doi: 10.1038/nature02114. [6] Steven W. Squyres. Icarus, 34(3):600-613, June 1978. doi: 10.1016/00 19-1035(78)90048-9. [7] Steven W. Squyres. Journal of Geophysical Research: Solid Earth, 84(B14):8087-8096, 1979. doi: 10.1029/JB084iB14p08087. [8] David M. H. Baker. Icarus, 207(1):186-209, May 2010. doi: 10.1016/j.icarus.2009.11.017. [9] Colin Souness. Icarus, 217(1):243-255, January 2012. doi: 10.1016/j.icarus.2011.10.020. [10] Joseph S. Levy. Journal of Geophysical Research: Planets, 119(10):2188-2196, 2014. doi: 10.1002/2014JE004685. [11] Crofton B. Farmer. Icarus, 28(2):279-289, June 1976. doi: 10.1016/0019-1035(76)90038-5. [12] Vincent Chevrier. Geophysical Research Letters, 34(2), 2007. doi: 10.1029/2006GL028401. [13] J. W. Head. Nature, 434(7031):346-351, March 2005. doi: 10.1038/nature03359. [14] John W. Holt. Science, 322(5905): 1235-1238, November 2008. doi: 10.1126/science.1164246. [15] Michael H. Carr. Journal of Geophysical Research: Planets, 106(E10):23571-23593, 2001. doi: 10.1029/2000JE001316. [16] Rishitosh K. Sinha. Planetary and Space Science, 86:10-32, September 2013. doi: 10.1016/j.pss.2013.09.002. [17] David M. H. Baker. Icarus, 260:269-288, November 2015. doi: 10.1016/j.icarus.2015.06.036. [18] Andreas Johnsson. pages EPSC2016-18181, April 2016. ADS Bibcode: 2016EGUGA..1818181J. [19] Savana Z. Woodley. Icarus, 386:115147, November 2022. doi: 10.1016/j.icarus.2022.115147. [20] J. L. Dickson. Earth and Space Science, 11 (7):e20 24EA003555, 2024. doi: 10.1029/2024EA003555. [21] Maria E. Banks. Journal of Geophysical Research: Planets, 113(E12), 2008. doi: 10.1029/2007JE002994. [22] A. S. McEwen. Icarus, 419:115795, September 2024. doi: 10.1016/j.icarus.2023. 115795. [23] N. Thomas. Space Science Reviews, 212(3):1897 –1944, November 2017. doi: 10.1007/s11214-017-0421-1. [24] C. Quantin-Nataf. Planetary and Space Science, 150:157–170, January 2018. doi: 10.1016/j.pss.2017.09.014. [25] Sarah S. Sutton. Remote Sensing, 14(10):2403, January 2022. doi: 10.3390/rs14102403. [26] Stuart J. Robbins. Journal of Geophysical Research: Planets, 117(E5), 2012. doi: 10.1029/ 2011JE003966. [27] David K. Weiss. Icarus, 233:131–146, May 2014. doi: 10.1016/j.icarus.2014.01.038.