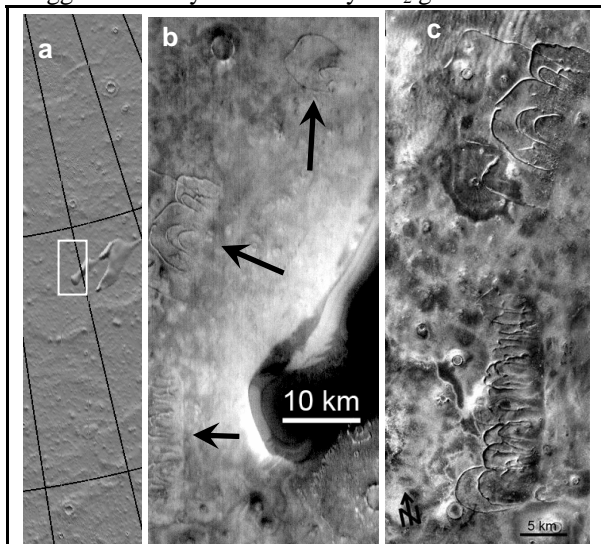


## CARBON DIOXIDE GLACIERS IN THE RECENT GEOLOGICAL HISTORY OF MARS?

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**Introduction:** Water ice is abundant on the surface and shallow subsurface in various locations on Mars, especially at high and middle latitudes. On the Earth, the most common ice morphologies are alpine glaciers and flowing ice sheets. Present-day Mars lacks such active features, which is a logical consequence of currently cold (unfavorable for ice flow) and dry (unfavorable for dynamic accumulation) climate conditions. Detailed studies, however, have revealed abundant morphologies suggestive of ice flow in the past. Three different types of ice flow morphologies have been identified on Mars ([1] and ref. therein): (1) small (100s m long, 10s m thick) lobes on steep slopes in mid-latitudes; (2) lobate debris aprons, lineated valley fill, concentric crater fill, features genetically similar to each other that are from 10s km of spatial extent to 100s km long, 100s m thick and arguably thicker in the past; (3) extinct tropical mountain glaciers, features of 100s km of spatial extent with inferred ice thickness of a few km during the epochs when they were active.

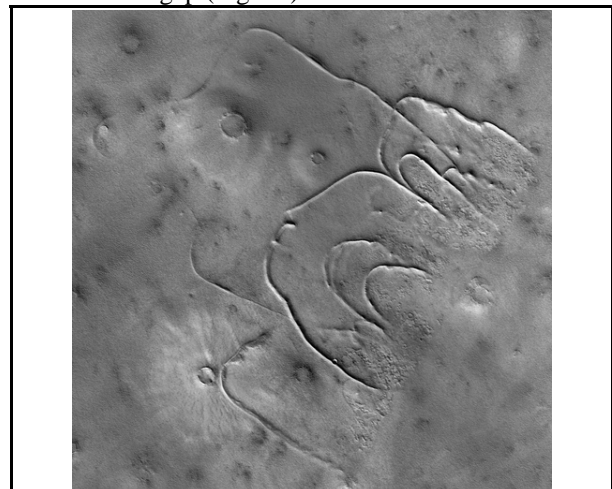
Here we report on one more type of distinctive glacial morphology on Mars. We show that these features cannot be formed by flow of H<sub>2</sub>O ice and suggest that they are formed by CO<sub>2</sub> glaciers.



**Fig. 1.** (a) Topography with frame (b); (b) THEMIS IR image I11693002; arrows show three groups of ridges; (c) THEMIS VIS image V11718001; middle and southern group of ridges.

**Morphology:** An unusual series of narrow ridges with lobate planforms occurs at high latitudes in the martian arctic (74°N 96°E), in association with the west- and northwest-facing steep slopes of an outlier of the polar layered deposits (PLD) (**Fig. 1**). Distinctive arch-like ridges (in planform view)

forming parallel and overlapping loops over a distance of about 75 km grouping in three sets with gaps between them (**Fig. 1b**). The individual ridges are 15-80 m wide, are generally continuous, and show little width and height variation along their strike. The loops formed by these ridges are most typically 5-7 km in long axis, and ~1.5-3 km wide. The ridges are superposed on impact craters and deposits associated with them; no evidence of modification of the underlying deposits or structures are observed; these all suggest a relatively youthful age. High-resolution HiRISE images (e.g., PSP\_007792\_2540) show that the ridges are mantled and covered with typical high-latitude polygonal pattern uniformly with their surroundings. Some of the ridges, and thus the loops, are superposed on one another. In the middle group (**Fig. 2**) a generally continuous ridge extends distally for a distance of up to 15 km; the ridge is subdued in some places along its strike. Shorter loops contained within this deposit are clearly superposed on this larger ridge complex occurrence. Stratigraphic relationships suggest that the earliest set of ridges was the broadest and reached the greatest distal limits. The proximal parts of the looped ridges are open toward the steep wall of the PLD outlier and are separated from it by a 10-20 km wide gap (**Fig. 1b**).

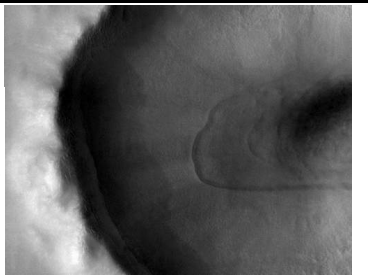


**Fig. 2.** Middle group of ridges. The scene (18 km wide) is covered by seasonal frost. CTX image P16\_007357\_2541.

Similar sets of lobate ridges occur in two more locations in martian arctic, both in impact craters (70.3°N, 266.5°E and 67.2°N 249.5°E). The first is described in detail in [2]; the second is shown in **Fig. 3**. In these craters, the lobes point to the west and open toward eastern inner crater walls. We do not know any other similar features on Mars.

**Interpretation:** These ridges, their looped configuration, their relationship to the substrate and the appearance of mutual superposition, are very similar to ridges typical of drop moraines in terrestrial cold-based glacial environments. These form when cold-based glaciers advance and then dynamically stabilize; in this case, debris carried forward by the glacier drops out at the glacial front as sublimation of the ice occurs and a drop moraine is produced [3]. Overlapping ridges are formed due to multiple episodes of glacier advance and retreat. For more detailed argumentation for the drop moraine mechanism see [2]. The gap between the PLD outlier wall and the ridges (Fig. 1b) was probably formed by later retreat of the PLD outlier due to sublimation. Interaction of the lobes and the central peak in the crater at 70.3°N, 266.5°E [2] give estimate of ~400m thickness of the glacier, when it was active.

**Fig. 3.** Central and western part of a crater at 67.2°N 249.5°E. THEMIS VIS image V05659020. The scene is 20 km wide.



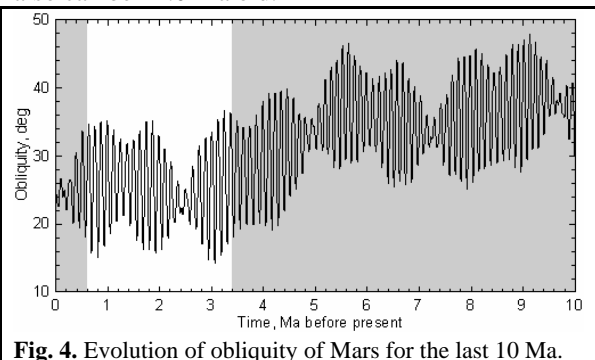
**Origin:** Although morphology unambiguously suggest cold-based glacier-like flow as origin of these features, flow of H<sub>2</sub>O ice would contradict observations: (1) At the same high-latitude location and hence the same temperature regime, the PLD material itself (which is known to be mostly H<sub>2</sub>O ice [4]) does not show any sign of flow forming small lobes. (2) mid-latitude lobate features are formed at higher temperatures (due to lower latitudes) and display total strain on the order of 1, while for the glaciers under consideration the total strain is 100s or more. (3) Tropical mountain glaciers that left drop moraines [5] and had a significant total strain, were an order of magnitude thicker and flowed under higher temperatures. Thus, the flowing material formed the drop moraines in the martian high arctic is much weaker and flows much easier than H<sub>2</sub>O ice under the same temperature regime.

We suggest that these drop moraines were formed by carbon dioxide (CO<sub>2</sub>) glaciers. We have predicted CO<sub>2</sub> glaciers to form on Mars during periods of low obliquity [6] due to accumulation of perennial CO<sub>2</sub> deposits in preferable locations at high latitudes. Solid CO<sub>2</sub> (dry ice) is softer (more plastic) than H<sub>2</sub>O ice at the same temperature. This explains the unusual rheology of the flow material.

Accumulation of solid CO<sub>2</sub> at low obliquity has been anticipated on pole-facing slopes, while the observed features clearly suggest accumulation on west- and northwest-facing slopes. Since CO<sub>2</sub> is the dominant component of the present-day atmosphere,

its accumulation is controlled primarily by direct heat balance, unlike solid H<sub>2</sub>O accumulation on the Earth, where microclimates may take control. Under very low obliquity, when a significant part of CO<sub>2</sub> inventory resides on the surface in high-latitude perennial deposits, the proportion of non-condensing atmospheric components (N<sub>2</sub>, Ar) is higher, and potential importance of microclimates for CO<sub>2</sub> deposition may increase. In addition, recent calculations of atmospheric photochemistry of Mars in a wide range of conditions [7] showed that when the atmospheric H<sub>2</sub>O vapor abundance is very low, a significant part of atmospheric CO<sub>2</sub> can be converted into CO and O<sub>2</sub> by photochemical processes. At low obliquity, the H<sub>2</sub>O vapor abundance is expected to be very low (all H<sub>2</sub>O is trapped in the perennially cold solid CO<sub>2</sub> deposits), and CO<sub>2</sub> may lose its dominance in the atmospheric composition, which would make accumulation on west-facing slopes plausible.

Calculation of spin and orbit evolution of Mars [8] shows that the obliquity was low (<18°) for a few short periods within 3.4 - 0.6 Ma ago (**Fig. 4**), and had not been low at least for a few 10s of Ma before that period. This gives rather certain age estimate of 0.6 - 0.8 Ma for the youngest drop moraines. The oldest ones may be as old as 3.4 Ma, but also can be ~1.0 Ma old.



**Fig. 4.** Evolution of obliquity of Mars for the last 10 Ma.

**Discussion:** The identification of CO<sub>2</sub> glaciers on Mars is not only interesting by itself; it has significant consequences for understanding recent climate-controlled processes on Mars. (1) Sets of the polygonal cracks in the high latitudes are superposed on the drop moraines and hence are younger than 0.6 - 0.8 Ma. (2) The PLD outlier existed at least 0.6 Ma ago and perhaps, 1.0 Ma ago. (3) Its wall retreated by 10 - 20 km during the last 0.6 Ma. This gives the time scale of shaping of the PLD troughs.

**References:** [1] Carr, M. (2006) *The surface of Mars*, Cambridge Univ. Press. [2] Garvin J. B. et al. (2006) *Meteoritics & Planet. Sci.*, 41, 10, 1659-1674 [3] Marchant D. R. et al. (1993) *Geografiska Annaler*, 75A, 303-330. [4] Grima C. et al. (2009) *GRL*, 36, L03203. [5] Shean, D. E. et al. (2007) *JGR* 112, E03004. [6] Kreslavsky M. A. and Head J. W. (2005) *GRL*, 32, L12202. [7] Zahnle, K. et al. (2008) *JGR* 113, E11004. [8] Laskar, J. et al. (2004) *Icarus* 170, 343-364.