UNUSUAL GLACIAL-LIKE FEATURES IN THE HIGH-ARCTIC OF MARS.

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Introduction: The recent advance in imaging of Mars confirmed that a number of previously hypothesized geomorphological feature types were related to ice flow, as well as revealed a variety of related new feature types. In the equatorial zone, the western slopes of the four major volcanoes bear a set of features interpreted as left by kilometers-thick cold-based ice sheets formed during epochs of high mean obliquity in the Amazonian [e.g., 1]. Martian midlatitudes display a very wide variety of features related to flow of ice or creep of permafrost; they include lobate debris aprons, lineated valley fill, slope-associated lobes interpreted as extinct or present rock and/or debris-covered glaciers, extinct ice sheets, etc. The abundance of such features in the midlatitudes is explained [2] by both relatively high year-average temperature, which enables flow of H_2O ice or icy permafrost, and relatively good conditions for ice stability. At high latitudes, H_2O ice is present in large amounts, forming the polar layered deposits (PLD) and the high-latitude ice-rich mantle, but ice flow is very limited. In general, this is naturally explained by the much lower year-average temperature at high latitudes. Here we describe very unusual deposits that depart from this general trend, and discuss their possible origin.

Unusual extinct small cold-based glaciers: 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 a PLD outlier (**Fig. 1**). The most striking aspect of these features is the large number of distinctive arch-like ridges (in planform view) forming more than 20 parallel and overlapping loops over a distance of about 75 km grouping in three sets with gaps between them (Fig. 1b). The individual ridges making up the loops 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. No impact craters could be found that were clearly superposed on top of the ridges; in several cases, the ridges in the distal parts of loops are superposed on the extended deposits surrounding impact craters; no evidence of modification of the underlying deposits or structures are observed; these all suggest a relatively youthful age. High-resolution MOC images (E03/01183, R02/01333) 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. 1c, top) a generally continuous ridge set that extends distally (with respect to the PLD outlier) 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 for the middle group suggest that the earliest set of ridges was the broadest and reached the greatest distal limits; an intermediate set extended only about 3 km, and the latest set extended an intermediate distance. In the southern group, local stratigraphic relationships also support three stages. 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.

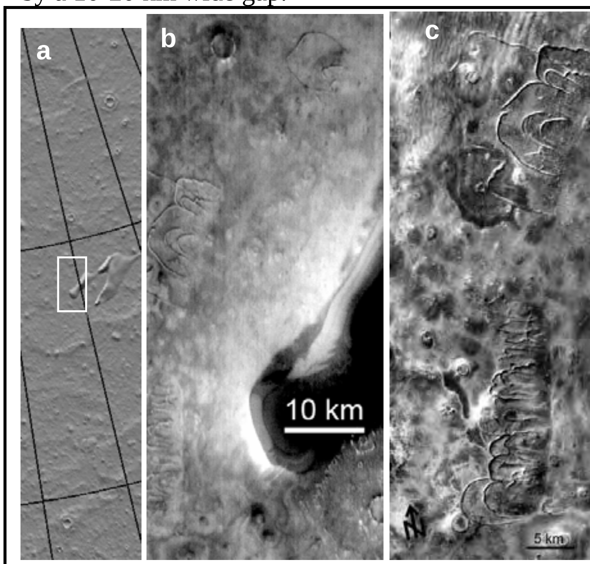


Fig. 1. (**a**) Topography with frame (b); (**b**) THEMIS IR image I11693002; (**c**) THEMIS VIS image V11718001.

These ridge-like features, their looped configuration, and their relationship to the substrate, are very similar to ridges typical of drop moraines in cold-based glacial environments. These form when cold-based glaciers advance and then dynamically stabilize (the ice advance rate equals the frontal ice ablation rate); 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 [3-4]. Similar features are seen in environments interpreted to be of glacial origin in several locations on Mars [1,5-7].

In this interpretation, glacial ice would have moved forward from the edge of the PLD outlier out; recession and readvance would have occurred at least once, then that the glacial ice retreated and vertically wasted away. The gap between the PLD outlier wall and the ridges was formed by later retreat of the PLD outlier due to sublimation (H_2O ice with an unknown proportion of dust is thought to be the PLD material).

H_2O: Water ice of the PLD outlier seems to be the obvious source of glacier material. However, this straightforward suggestion does not fit all observations. The elongate lobate planform of the ridges strongly suggests large total strain and high strain rates. The large total strain and lobate flows are not completely consistent with the perfectly parallel horizontal layers currently exposed on the PLD outlier walls. High strain rates imply high year-average temperature, which is not easy to arrange in the high latitudes, even under high obliquity. The cold-based nature of the glaciers is not fully consistent with high strain rates. It is difficult to explain the absence of similar deposits on the other sides of the PLD outlier and elsewhere in high latitudes in association with the main PLD. The observed morphology is much more consistent with accumulation of frost and snow forming soft ice on a steep slope of the outlier and its flow down the slope. In this case the local occurrence of the glaciers is easily explained by specific microenvironment (wind regime, etc.) favoring accumulation. But this is possible only if either (1) the PLD outlier is made of unknown material much stronger than water ice, or (2) the flowing material is not water ice, but some other substance able to condense, accumulate and form soft glaciers on stronger slope of the icy outlier. Below we explore alternative options.

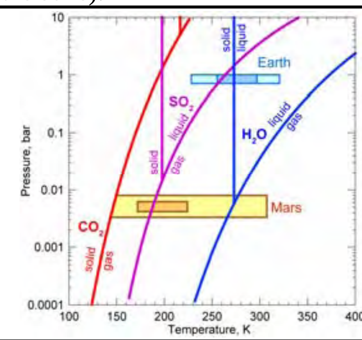
CO_2: We have predicted glaciers made of solid carbon dioxide on Mars [8]. At low obliquity the atmospheric CO_2 condenses to make perennial deposits. Solid CO_2 is much softer than H_2O ice. The absence of a liquid phase at these surface conditions is consistent with the cold-based glacier morphology. The only, but serious problem with CO_2 glaciers is that solid CO_2 accumulation at low obliquity would occur at north-facing slopes [8], while here we observe ridges on west-facing slopes. CO_2 is a major component of the atmosphere, its deposition is controlled predominantly by energy balance, and local microenvironments play only a minor role and cannot account for a "wrong" slope orientation (for minor components of the atmosphere, local conditions may play a dominant role).

Thus, the glacier material should be less volatile (have lower saturation vapor pressure) than CO_2, and be soft in the solid state. Since such material is presently absent from the martian atmosphere, plausible sources and sinks should exist. Among a wide variety of simple inorganic and organic compounds, we found only one reasonable candidate, sulfur dioxide SO_2.

SO_2: Phase diagrams of SO_2, H_2O and CO_2 are shown in **Fig. 2** along with the limits of actual and year-average surface temperature and pressure. SO_2 is very volatile; formation of perennial deposits probably demands a little lower obliquity and is possible at high latitudes only. The high triple point pressure precludes liquid SO_2 at the surface and is consistent with the absence of any observed sign of liquid flow in association with the peculiar ridges. We failed to find any publications on rheology of solid SO_2, however, because of its low melting point, solid SO_2 is certainly much softer than H_2O ice under the same temperature.

Volcanic gases are an obvious source of SO_2. A reasonably voluminous volcanic event, e.g. 100 m thick lavas over the Cerberus plains, would release as much as ~1 mm equivalent global layer of SO_2, assuming 0.3 wt % SO_2, a "typical high" content for terrestrial basaltic magmas. A chain of photochemical reactions in the atmosphere oxidizes gaseous SO_2 to SO_3, which picks up water vapor to produce sulfuric acid H_2SO_4, which, in turn, precipitates and forms sulfates (found in significant amounts in Mars soils).

Fig. 2. Phase diagrams of CO_2, SO_2, H_2O; boxes show ranges of surface conditions and year-average surface conditions on Mars and the Earth.



A serious problem with SO_2 glaciers is that the removal process is too quick. Estimates [9, 10] give a 40 day lifetime of trace amounts of SO_2 in the present atmosphere, which is 3 orders of magnitude shorter than necessary for the glacier life cycle. Larger amounts of SO_2 and lower obliquity would extend this time, but special calculations are necessary to determine if the lifetime can be long enough.

Conclusions: We interpret the very unusual features in Fig. 1 as drop moraines left by extinct cold-based glaciers. The unusual characteristics of these deposits point to unusual materials and/or unusual conditions forming the glaciers. We consider water, carbon dioxide and sulfur dioxide. None of these materials provide a 100% satisfactory explanation for the features observed.

References: [1] Shean, D. et al. (2005) JGR, 110, E05001, doi:10.1029/2004JE002360. [2] Carr M. (1997) Water on Mars. [3] Marchant, D. and Head, J. (2007) Antarctic Dry Valleys: Microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars, *Icarus*, in revision. [4] Marchant, D. et al. (1993) *Geografiska Annaler*, *75A*, 269-302. [5] Head, J. and Marchant, D. (2003) Geology, 31, 641-644. [6] Shean, D. et al., Recent glaciation at high elevations on Arsia Mons, Mars: Implications for the formation and evolution of large tropical mountain glaciers, *JGR*, in press, doi: 10.1029/ 2006JE002761. [7] Garvin J. B. et al. (2006) *Meteoritics & Planet. Sci.*, 41, Issue 10, p.1659-1674. [8] Kreslavsky M. A. and Head J. W. (2005) *GRL*, *32*, L12202. [9] Wong, A.-S. et al. (2003) *JGR 108*, 5026, doi:10.1029/2002JE002003. [10] Wong, A.-S. et al. (2004) *JGR 109*, E01007, doi:10.1029/2003JE002210.