Morphological study of glacial features at Protonilus Mensae, Mars and their analogues in Ladakh, India.

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Introduction: Glaciers are large (kms scale) bodies of ice formed due to long-term accumulation and compaction of snow that modifies the landscape upon movement depending on their size and extent. On Mars glaciers are present as large swirling bodies at the poles in the current climatic conditions whereas, Earth hosts glaciers at its poles as well in the high altitude-low latitude regions (as low as mid-latitudes and sub-tropics). The current climatic conditions of Mars do not favor the accumulation of snow except at the poles, yet various features and landforms of varying sizes and extent similar in morphology to the glacial features on earth are present in the mid-latitudes of Mars reaching as low as 30°N and S [1, 2]. It suggests that the paleo-climatic conditions once favored supply and accumulation of snow in these regions. During the late Amazonian, Mars underwent multiple shifts in the axial tilt which aided the supply of snow and after combining with dust in the atmosphere got deposited as dust-ice mantle and further got covered in debris [2]. This ice, covered in debris starts flowing downslope and, in the process, gives rise to viscous flow features such as Lobate Debris Apron (LDAs), Lineated Valley Fill (LVF), Glacier Like Form GLF and Moraine Like Ridges (MLRs) [2, 3, 4], These features form a large cluster in the northern mid-latitudes and most of them are present in fretted terrain at Deuteronilus Mensae and Protonilus Mensae [4]. Morphological study of rock glaciers and their comparative analysis on Mars and earth can improve our understanding about the past and present climatic conditions of Mars with possible implications for Earth. This study therefore, attempted to observe and analyze the glacier features of Mars and Earth present in similar latitudes as possible analogous regions using high-resolution satellite data.

Study areas: The regions Protonilus Mensae and Ladakh, India (Figure 1) are present in similar latitudes on Mars and Earth, respectively. The Martian study site was selected since the region lies in the fretted terrain which is highly altered possibly due to multiple glaciations. Similarly, Ladakh Himalayas are also majorly modified due to glacial activity with a very high preservation potential of glacial features due to its geographical location, climate and barren landscape.

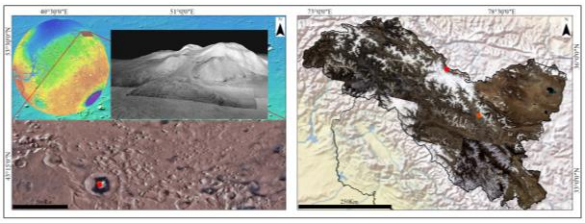

Figure 1: Location of Study area Protonilus Mensae (left) of Mars with a 3D inset of the central peak of Moreux crater. Landsat-9 true color image of Ladakh, India (right side) (modified after [3]). The orange and red markers in the map indicates the location of the features in figure 2 and 3 respectively.

Datasets and Methodology: To analyze the geomorphic features from Protonilus Mensae high-resolution optical datasets from the High-Resolution Imaging Science Experiment (HiRISE) [5] with a spatial resolution of 30cm/pixel and images from Context Camera (CTX) [6] with the spatial resolution of 6m/pixel were used. Viking and MOLA colorized global mosaics by NASA AMES were used to prepare the base map of Protonilus Mensae. Datasets from Orbview High-Resolution Imaging system (OHRIS) onboard Orbview-3 satellite with a spatial resolution of 1m/pixel in panchromatic band and images from Google Earth base map for unavailable features were used for morphological analysis of glacial features in Ladakh. Landsat 9 images were used to create the base map of Ladakh. Various features of glacial origin were taken into consideration for morphological comparison to understand the similarities among them and high-resolution satellite images of the selected glacial features present on both planetary bodies have been utilized to establish morphological similarities.

Observation and Discussions: With the use of high-resolution information, a variety of debris-covered areas on the Martian surface may be seen that resemble the rock glaciers in Ladakh. The representation in figure 2(left) is of the central peak of Moreux crater where the accumulation zone at the top of the peak appears similar to terrestrial cirques, debris moves downslope eroding additional material and gets deposited at the base where the gradient decreases, this deposited debris get crumpled due to the pressure exerted by the transported debris. Similarly, in figure 2 (right) the same mechanism can be observed with complex crumpling in

Ladakh.

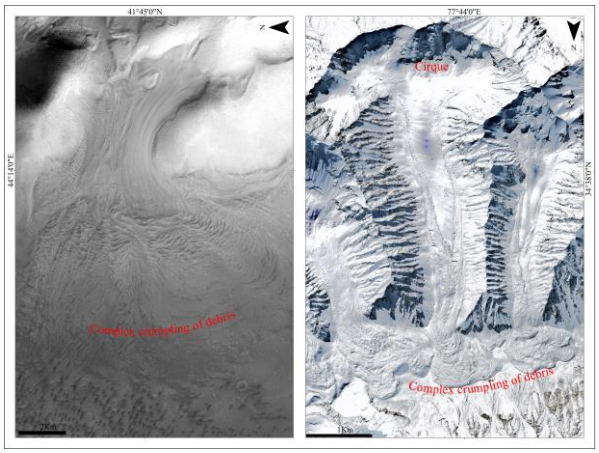

Figure 2: CTX image B06_011974_2220_XI_42N315W (left) shows a debris-covered glacier forming a series of ridges due to crumpling. (Right) Rock glaciers of Ladakh with similar crumpled ridges, (modified after [3]).

Figure 3 (both left and right) shows a typical tongue-shaped lobe at the base of the hill, both bordered by arcuate ridges at the apex and linear ridges at its sides similar to terminal and end moraines, respectively. The morphological similarities between these landforms point to a common method of formation in which the debris is lubricated with interstitial ice and also helps in its downward motion, much like the rock glaciers of Ladakh.

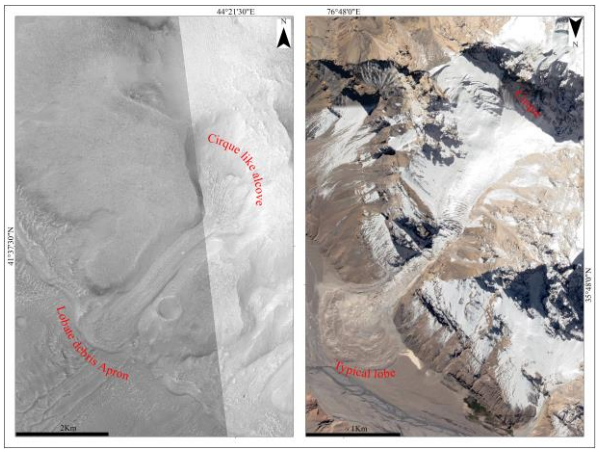

Figure 3: Left- a mosaic of HiRISE images ESP_060197_2220_RED and PSP_002098_2220_RED showing LDA at the base. Right- terrestrial tongue-shaped lobe, (modified after [3]).

Climatic variability and implications: Morphology of the features of glacial origin formed on Mars vary depending upon the axial tilt of Mars, where the size and extent of these features increase or decrease based on the intensity of glaciation during glacial maxima and minima which in turn is related to obliquity regimes [2, 7] of the planet, this can be observed from the features at Protonilus Mensae where smaller features are superimposed on wider large scale features indicating a shift in glaciation form colder to comparatively warmer climate [7]. Similarly, Moraines in the Ladakh region were dated, and was found that some of the oldest moraines from late Quaternary glaciation are present in Ladakh. These moraines also showed variation in their size and extent such that older ones were bigger in size suggesting a shift in climatic conditions from glacial maxima to minima [8]. This shift in Earth's climate from colder to warmer periods could be attributed to many endogenic factors and exogenic factors such as earth's orbital parameters. Milutin Milankovitch considered changes in Earth's orbital parameters an important factor for variation in its climate and attributed the periodicity of glaciation to these factors [9].

Conclusion: Features of glacial origin are present in the valleys and along the slopes of mesas arising from the cirque-like alcoves in Protonilus Mensae. There are also numerous glacial features in Ladakh Himalaya with striking similarities to their Martian counterparts. Detailed studies of such features in Ladakh Himalaya while keeping in mind the climatic conditions and their variability can help us understand the possible geological processes during Mars' glacial past. Ladakh, a high-altitude cold desert in the western Himalayan region can serve as an analogous site for Mars, and studying analogous sites having geographical and geological similarities could be the best possible way of understanding the past climatic conditions and surface processes on Mars.

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