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Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change

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Abstract

Understanding spin orbital parameter-driven climate change on Mars prior to ~ 20 Ma ago requires geological evidence because numerical solutions for that period are chaotic and non-unique. We show geological evidence that lineated valley fill at low mid-latitudes in the northern hemisphere of Mars (~ 37.5° N) originated through regional snow and ice accumulation and underwent glacial-like flow. Breached upland craters and theater-headed valleys reveal features typical of erosion in association with terrestrial glaciers. Parallel, converging and chevron-like lineations in potentially ice-rich deposits on valley floors indicate that flow occurred through constrictions and converged from different directions at different velocities. Together, these Martian deposits and erosional landforms resemble those of intermontaine glacial systems on Earth, particularly in their major morphology, topographic shape, planform and detailed surface features. An inferred Late Amazonian age, combined with predictions of climate models, suggest that the obliquity of Mars exceeded a mean of 45° for a sustained period. During this time, significant transfer of ice occurred from ice-rich regions (e.g., the poles) to mid-latitudes, causing prolonged snow and ice accumulation there and forming an extensive system of valley glaciers.

Keywords: Mars; glaciation; lineated valley fill; climate change; Deuteronilus Mensae

1. Introduction

Recently, new spacecraft data for Mars Global Surveyor and Mars Odyssey, and insight into the nature of glaciation in Mars-like hyperarid cold polar deserts on Earth (e.g., [1]) have supported earlier hypotheses [2] that glaciation might have occurred on Mars in non-polar regions. New solutions and predictions for historical variations in the spin orbital parameters of Mars [3] show that the obliquity of Mars varied significantly from its present unusually low value (25.19°). These new solutions permit robust predictions of parameter variations over the last ~ 20 Ma, but prior to that time the solutions are chaotic and non-unique. The solutions predict that the maximum obliquity over the history of Mars may have reached 82°; the standard model of insolation parameters [3] over 4 Gyr predicts a most probable obliquity value of ~ 46°. Due to the non-uniqueness of solutions for orbital parameter variation during this time, one must rely on the geological record to provide evidence for the nature of climate change. Furthermore, atmospheric general circulation models

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taking into account the redistribution of polar volatiles and water vapor in the atmosphere equator-ward during periods of high obliquity predict deposition and retention of ice and snow at lower latitudes during these times [4–7]. Thus, it is appropriate to examine the geological record for evidence of the former presence of water and ice at mid-latitudes as one key indicator of volatile transport, climate change, and orbital parameter variation. Here we examine mid-latitude lineated valley fill to assess the presence and state of water in its formation and evolution in order to address the issue of past climate change.

Among the hallmark morphologies of the highland–lowland boundary region in the northern mid-latitude Deuteronilus–Protonilus Mensae area (30–50° N, 10–45° E) (Fig. 1) is the fretted terrain [8], consisting of (1) debris aprons that surround many of the massifs and valley walls and (2) lineated valley fill that occurs on the floors of many of the valleys [9–20]. The ages of these deposits are typically much younger than the adjacent plateau terrain or its breakup and the formation of the valleys themselves (e.g., [10,20]). The margins of the debris aprons consist of rounded and convex upward topography, and at Viking resolution the debris aprons and the valley fill can appear smooth and relatively homogeneous or, in contrast, can be characterized by closely spaced parallel ridges and grooves a few to several tens of meters high. Some workers (e.g., [8]) argue that the valley fill lineations form mostly normal to the direction of flow due to converging flow from debris aprons on opposite sides of valleys or mesas, while others (e.g., [2]) argue that bending of ridges and grooves entering valleys from a side tributary supports flow in the direction along the valley. Recent analysis also reveals that lineated valley fill displays topographic slope reversals, interpreted to mean that along-valley flow was minimal [17]. All agree that the materials represent some sort of viscous flow processes, but opinions differ on the details of the mechanism; most authors call on processes of gravity-driven debris flow,

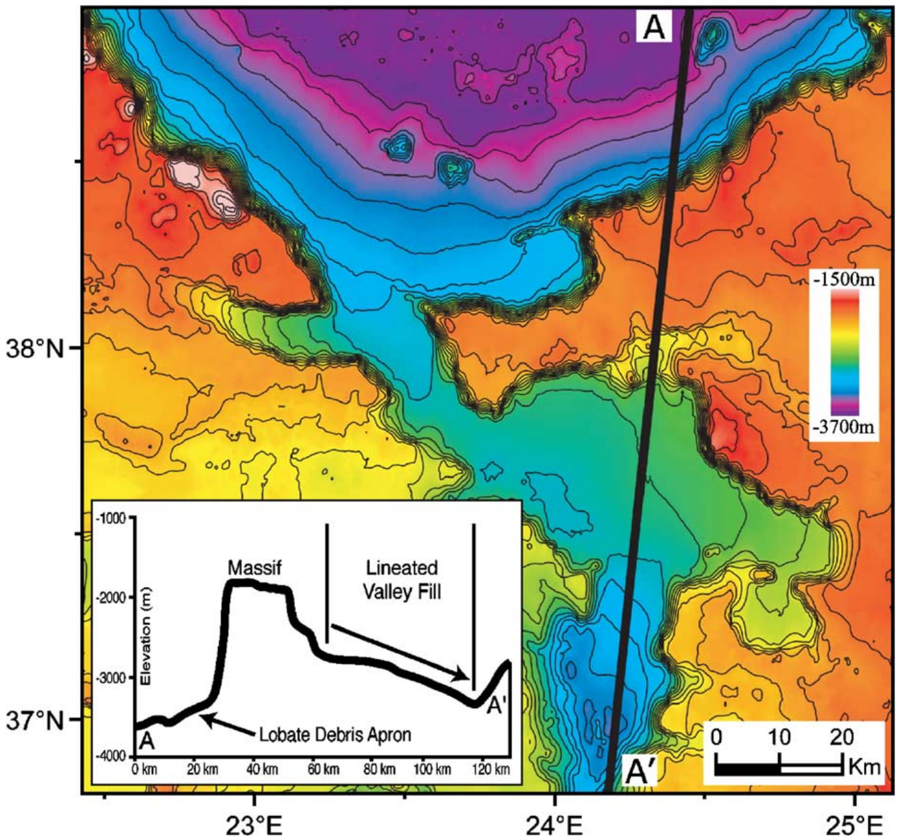


Fig. 1. Color-coded MOLA altimetry map with superposed 100-m contours; line A–A′ shows the location of an approximately N–S profile from MOLA 128 pixel/degree gridded data. Altimetric profile (inset) shows decreasing topography of the lineated valley fill in the interpreted direction of flow. Sinusoidal projection.

assisted by ice or water in the debris interstices, derived from either groundwater or diffusive water vapor exchange with the atmosphere (e.g., see [13,16,19,20]). Some liken the process to rock-glacial flow (e.g., [2,9]) with the source of the major deforming agent being ice from atmospheric frost deposition and diffusion into rock debris pore spaces [9] or, alternatively, mobilized interstitial ground ice [2]. In this contribution, we assess whether glaciers, derived from snowfall, may have been a factor in the formation of lineated valley fill.

What criteria for the recognition of glaciers, past and present, can be employed in order to examine this possibility? Four types of observations can provide insight into the distribution of glacial-erosional landforms and deposits [21]: (1) presence of the major morphologies and zones typical of glaciers (e.g., accumulation and ablation zones), (2) topographic variations (convex-upward profile and generally sloped in a down-flow direction), (3) planform (e.g., source regions, tributaries, convergence zones, main trunk valleys, etc.), and (4) surface features (e.g., lineations, crevasses, lateral, medial and terminal moraines, evidence of converging flow and surface deformation, etc.). We analyzed new THEMIS (Mars Odyssey), MOLA and MOC (Mars Global Surveyor) data to assess the nature and origin of lineated valley fill, and found evidence that glaciation (accumulation of snow and ice to sufficient thickness to cause its local and regional flow) has played a significant regional role in its formation.

1.1. New observations

We have analyzed numerous areas along the dichotomy boundary north of 30°N latitude and present in detail the results from an area in southern Deuteronilus Mensae, where a T-shaped valley occurs just south of a large depression (Fig. 1). The walls of the large depression are characterized by debris aprons and there is a break in the southern rim of the depression that leads to the top of the T-shaped valley about 100 km across. A topographic profile (Fig. 1) from the floor of the large depression across the southern wall, across the top of the T and along the meridional part of the T shows (1) the flat floor of the large depression, (2) a pole-facing convex-upward slope of the debris apron, (3) the elevated floor of the generally WNW-trending top of the T, and (4) the convex-upward slope of the generally NS-trending meridional part of the T. Note that the floor of the T-shaped valley along the top of the T lies at elevations as high as −2600 m, almost 1 km above the large depression floor. The bottom of the valley along the vertical part of the T lies ~ 500 m below the valley floor at the top of the T, implying a thickness of the valley fill in excess of hundreds of meters.

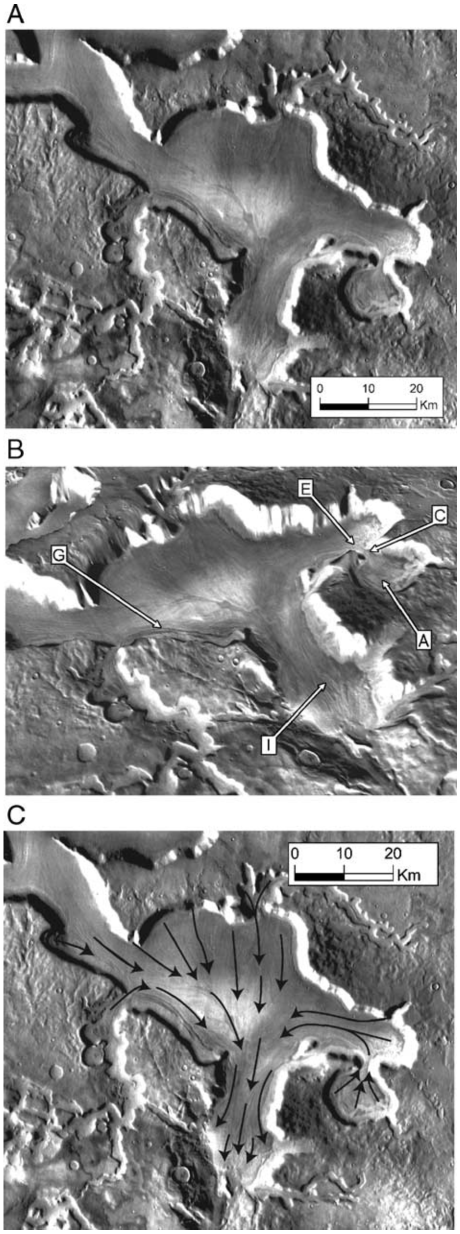
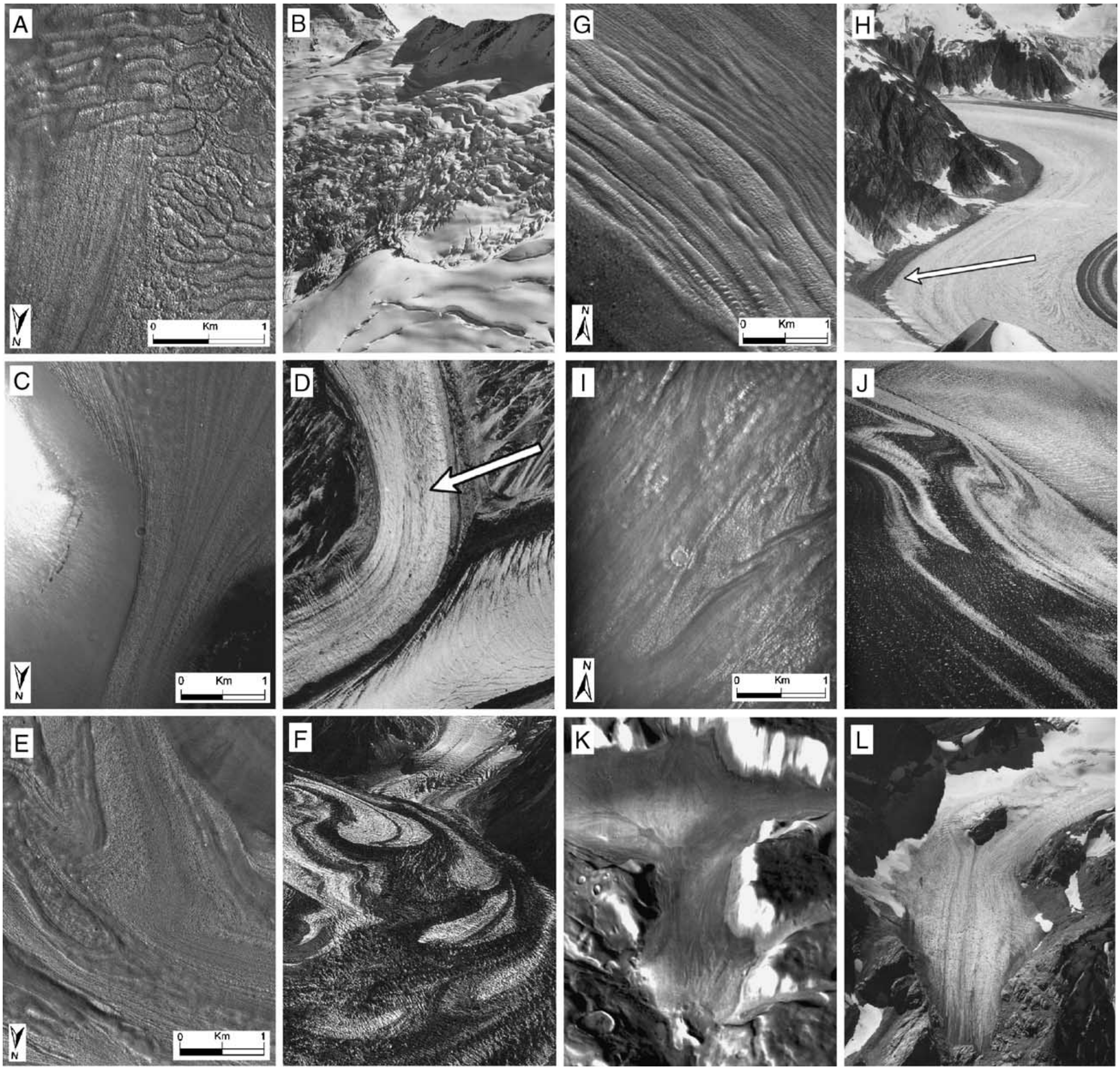


Fig. 2. (A) THEMIS daytime IR image mosaic showing the T-shaped valley, the lineated valley fill contained within it, and the surrounding plateau. (B) THEMIS mosaic overlain on MOLA topographic map and viewed perspectively from the southwest. Vertical exaggeration is ~7.5×. Letters show location of detailed MOC images in Fig. 3. Sinusoidal projection. (C) THEMIS mosaic with major flow trends highlighted by arrows. Flow emerges from breached craters, tributary valleys, and indentations in valley walls.

THEMIS image data (Fig. 2A) superposed on MOLA altimetry and viewed perspectively show lineations typical of valley fill (Fig. 2B), their characteristics and their directions of flow; details of the lineations are shown in MOC images and compared to terrestrial glacial features (Fig. 3). Examination of Figs. 1 and 2 shows a 15-km-diameter breached crater south of the eastern arm of the T (Fig. 2B, arrow A). At the southern interior wall of the crater, material is banked up against the wall and shows evidence of flow lineations extending away from the wall. Elongated slab-like features lie parallel with the wall and are separated by linear troughs (Fig. 3A). These features are very similar to bergschrunds (fractures separating flowing from stagnant ice) and seracs (isolated ice blocks) seen in terrestrial accumulation zones [22] (Fig. 3B). The presence of these characteristic features here, but the lack of smooth deposits typically seen in terrestrial ice accumulation zones, suggests that snow, if present at one time, no longer covers the surface, most likely having sublimed away. Downslope, the elongated slabs give way to numerous lineations on the floor of the crater (Fig. 2B, arrow C); these trend away from the southern crater wall, converge (Fig. 3C,D), and can be traced through the gap in the crater wall, joining lineations beginning at the eastern edge of the T (Figs. 2B, arrow E; 3E). This configuration is typical of constricted flow and convergence between ice masses moving at different velocities, causing chevron-like shear patterns [23]



(Fig. 3D–F). Similar lineated valley fill extends from the mouth of a north-trending valley in the lower western part of the T (Fig. 2), is deformed by lineations from valley fill moving from the higher terrain to the west, and then joins the general lineated valley fill just to the east (Fig. 2B arrow G; Fig. 3G and H).

Along the southern margin of the western part of the T (Figs. 1 and 2), a portion of the lineated valley fill lies at the edge of the valley floor, but topographically above the central lineated valley fill (Fig. 2B, just below arrow G). The floor lineations are seen to be ridges interpreted to be debris-rich medial moraines (Fig. 3G and H). The terrace-like feature is typical of marginal stagnant portions of glacial flow on Earth which form and are isolated by changing flow dynamics (Fig. 3H, arrow). In terrestrial glaciers, this detachment and isolation usually occurs during the lowering of the central glacial surface, shear separation, and isolation of the marginal terrace due to the establishment of a new flow margin [24].

At the western part of the top of the T, additional lineated valley fill begins at the base of the broad amphitheater and converges at the T-junction with the lineated valley fill coming from the west and the east (Fig. 2A and B). From here, these three major flow lineation directions, together with several smaller ones (Fig. 2C), converge and extend down the vertical part of the T, with many of the lineations contorted within the area of the convergence (Fig. 2B, arrow I; Fig. 3I and J). At the end of the major lobe, the topography is broadly convex upward (Fig. 1) and the perspective view (Fig. 2B) shows the distinctive lobe-like nature of the valley fill as it extends into the adjacent low-lying terrain, displaying morphological relationships similar to distal glacier deposits in terrestrial environments (Fig. 3K and L).

1.2. Origin of Lineated Valley Fill

What processes are responsible for the valley fill? We see evidence in the lineated valley fill for features typical of terrestrial valley glaciers [21] (e.g., crevasses at accumulation zones and between ice moving at different velocities, tributaries converging toward main trunk valleys and generating lineated debris bands, some of which show surface convolutions suggestive of flow deformation, convergence zones, converging flow and surface deformation, and lateral and medial moraines). Thus, the lineated valley fill and its complex patterns (Fig. 2C) resemble flow lines in glacial ice on Earth, particularly where glacial ice converges from different directions at different velocities and deforms into complex patterns (Fig. 3C, E, and I). Detailed analysis of the MOC, THEMIS and MOLA data suggests that changing environments and local topographic conditions (such as the crater walls and the narrow valleys) favored accumulation and preservation of snow and ice, and its glacial-like flow down into surrounding areas for distances approaching 70 km (Fig. 2B and C). Such local ice accumulation zones are typical of debris-covered glacial flow in the Antarctic Dry Valleys [25], a cold polar desert analogous to the environment on Mars [1], and of regional valley glaciers and plateau icefield landsystems in Baffin and Ellesmere Islands [26,27] in the Canadian Arctic. For example, the regional valley glaciers associated with the Ellesmere Island plateau icefield landsystem show very similar relationships of accumulation zones, valley fill and down-valley flow, and convergence and ice flow deformation (compare Figs. 2 and 4).

Alternative hypotheses for the origin of lineated valley fill focus on transport inward from the valley

Fig. 3. High-resolution MOC images showing details of the lineated valley fill, the interpreted position in the glacial system, and terrestrial glacial analogs [38]. For locations, see letters in Fig. 2B. (A and B) Upper accumulation zone: MOC image R0400308 showing deformation of tabular blocks at the crater wall margin and downslope streaming and deformation of blocks. Compare to bergschrunds, accumulation zone crevasses, and seracs in the Bishop Glacier, Coast Mountains of British Columbia [38] (view is several hundred meters across). (C and D) Constriction at the mouth of the breached crater and convergence of flow lines: MOC image R0301488. Compare to narrowing of valley walls and constriction of flow lines (arrow), Yentna Glacier, Alaska Range [38] (view is several kilometers across). (E and F) Convergence and folding: MOC image R0301488 showing convergence of flow from two different directions (crater floor and alcove at east end of the T valley); where lineations meet, distinctive folding is observed, suggesting different velocities for the two ice flows. Looped and folded moraines, Yanert Glacier, Alaska Range, resulting from glacial surges [38] (view is several kilometers across). (G and H) Medial and lateral moraines and stranded marginal deposits: MOC image E1103966 showing linear ridges interpreted to be medial moraines formed into ridges by preferential sublimation of intervening, more ice-rich material. Also observed is a marginal dark terrace (lower left) interpreted to be a marginal deposit stranded along the lower valley wall by preferential lowering of the glacier interior. Compare to medial and lateral moraines and terraces (arrow), Speel Glacier, Coast Mountains, southeast Alaska [38] (view is several kilometers across). (I and J) Convergence, folding and shear: MOC image E0302127 showing very tight folds in the zone where valley ice flows from the upper part of the T are converging and deforming within the narrower valley (Fig. 2B). Compare to convergence and deformation of ice in the Bering Glacier, south central Alaska [38] (view is 4–5 km across). (K and L) Lobate lineated valley fill and glacial front: Perspective THEMIS mosaic view of lobate front of the lineated valley fill deposit (Fig. 2). Compare to the retreating glacier tongue showing the lineated nature of surface, and lateral spreading of tongues into topographic reentrants, Honeycomb Glacier, North Cascade Range [38] (view is several kilometers across).

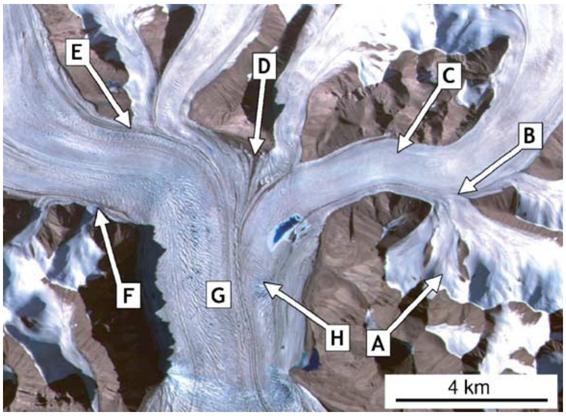


Fig. 4. Eugenie Glacier, Agassiz Ice Cap, Ellesmere Island, Canada, just north of Dobbins Bay (79°53′N, 75°10′W) showing a portion of the margins of the plateau icefield landsystem [31]. Width of image is ~ 13 km. Area A shows a series of cirque-like accumulation zones and converging flow toward the breach in the valley wall; compare to areas A and C in Figs. 2B and 3. Area B shows constriction and converging flow of two ice masses and associated deformation; compare to Areas C and E in Figs. 2B and 3. Area C contains ridges and moraines parallel to the valley and formed by converging ice masses; compare to similar areas in Figs. 2 and 3G. Areas D and E show medial moraines that form at the convergence of two ice tributaries; compare to the feature in Fig. 2B in the valley at the promontory just below the letter G. Area F shows two small glaciers joining the large valley glacier and the compression of the ice flow into a narrow band along, and slightly above, the valley margin; compare to Areas G in Figs. 2B and 3. Area G and H show the convergence of ice flow into the southerly trending broad Eugenie Glacier; note the deformation at G and H, and compare to I in Fig. 2B and Fig. 3I, K, and L. Advanced Thermal and Reflection Radiometer (ASTER) image obtained 7/31/00.

walls to form the lineations, and minimal subsequent down-valley movement (e.g., [9,17]). The evidence documented here in the higher resolution THEMIS and MOC data strongly suggests an integrated flow network; although flow may in places start at crater and valley walls and move toward valley centers, the predominant flow is along-valley. The variable and undulating along-valley topographic profiles typical of lineated valley fill (reversing gradients) have been cited as evidence that flow is more likely to be locally across-valley rather than systematically along-valley [17]. The integrated pattern of flow lineations documented in the new data (Fig. 2B and C), however, strongly supports along-valley flow, but also show that local accumulation zones and trunk valley convergence can produce along-valley topographic undulations. Furthermore, subsequent loss of volatiles and variation in the thickness of protective sublimation tills will enhance along-valley topographic variations.

Additional arguments against along-valley flow have included observations that lineated valley fill is found in valleys enclosed at both ends, and that floor textures of lineated valley fill often mimic the shape of valley walls [8]. Both of these observations are consistent with the glacial hypothesis. For example, enclosed valleys can contain multiple accumulation zones and the resulting lateral flow in the enclosed depression is accommodated by sublimation and volatile mass loss. Furthermore, accumulation zones can occur along valley walls if the geometry is conducive to preferential accumulation of snow and ice; lineated deposits that mimic wall topography can then be produced as ice moves onto the valley floor. In addition, along-valley flow will produce lineations that reflect the basic topographic characteristics of the valley walls.

Most alternative theories to glaciation for the origin of lineated valley fill call on lubrication and flow of rock debris and focus predominantly on groundwater, ground ice or ice from atmospheric water vapor diffusion as the origin of the lubricant (e.g., [2,9,13,16,19,20]). While such processes are likely to occur (for example, near-surface groundwater flow was probably more important in the Noachian, prior to about 3.7 Gyr ago, when the geothermal heat flux was much higher), we believe that the great lateral extent, continuity and direction of flow lineations, and their complex interactions consistent with glacial-like flow, are all evidence that supports glacial-like flow of debris-containing ice as the dominant process in formation of lineated valley fill in this region, rather than local flow of debris with an icy component in pore spaces originating from simple atmospheric water vapor diffusion.

The relationship between the lineated valley fill and the lobate debris aprons is not yet firmly established; however, the contiguous nature of many examples of lineated valley fill and debris aprons (Fig. 1) suggests that if the glacial interpretation of the valley fill is supported by further observations, then glacial ice may play more of a role in the formation of debris aprons than previously suspected (e.g., [28]).

2. Discussion and implications

Breached upland craters and theater-headed valleys reveal features typical of terrestrial intermontaine glacial settings, parallel lineations on valley floors resemble flow lines in glacial ice, converging lineations resemble ice flow through constrictions, and complex chevron-like flow patterns occur where lineated valley fill converges from different directions (Figs. 2 and 3). This example in the Deuteronilus Mensae region shows an integrated pattern (Fig. 2B and C) interpreted to represent snow and ice accumulation and along-valley flow for ~ 70 km. These patterns resemble valley glacial systems on Earth in major morphology, topographic shape, planform and detailed surface features (compare Figs. 2–4).

The current atmosphere and insolation conditions on Mars are not conducive to snow and ice accumulation at these latitudes [29]. Recent developments in the modeling of the orbital parameter variations thought to be the drivers of climate change on Mars [3] have shown that robust predictions can be made only back to ~ 20 million years before the present. Therefore, geological evidence is required to help distinguish among the family of plausible orbital parameter histories. The data presented here imply that, earlier in the Late Amazonian period (which extends from ~ 400 million years ago to the present), significant climate change occurred which caused sustained snow and ice accumulation and flow at mid-latitudes to form a regional system of valley glaciers. Due to protective sublimation tills, some of these features may still be cored with glacial ice.

The age of similar deposits elsewhere in this region have been estimated to be Late Amazonian (~ 300 Ma, with some of the deposits as young as 10 Ma) [20]. This suggests that there may have been periods during the Amazonian when mid-latitude glaciation was extensive. What might the mid-latitudes of Mars have looked like during these periods? In the Deuteronilus region (Figs. 1, 2) local accumulation zones in breached craters and tributary valleys clearly fed the glaciers. In some areas of the lineated valley fill in this latitude range, evidence has recently been presented that valleys containing lineated valley fill were once filled with ice which overflowed and extended out onto the marginal plateaus, leaving deposits after they receded back down into the valleys [30]. The distribution of ice on the Ellesmere Island Agassiz Ice Cap, a plateau icefield landsystem [31], is an instructive example (Fig. 4). Accumulation zones include large expanses of adjacent high plateaus characterized by ice caps which then flow down into preexisting valleys into a marginal series of converging valley glaciers, that ultimately sublime and melt or sometimes extend out onto surrounding plains to produce local piedmont glaciers. Furthermore, on Mars, recent modeling of glacial flow in lineated valley fill suggests that the distribution of snow and ice would be much more likely to include regional ice deposits feeding valley fill and that the current valley fill configuration may be the remnants of a more extensive regional ice sheet [30].

What would cause the formation of regional snow and ice deposits at these latitudes during the Late Amazonian? Recent advances in global climate modeling have permitted the examination of the fate of volatiles such as H_2O in response to changes in global patterns of orbital parameter-driven insolation. These studies [4–7] show that at obliquities of 45° or more, water vapor mobilized from the polar regions is redistributed at mid-latitudes, is stable there as ice, and will accumulate if obliquity remains at these values. Although robust prediction of obliquity beyond ~ 20 Ma is not possible, statistical studies of the possible behavior of obliquity over the last 250 Ma have been performed [3] and the range of solutions include scenarios from about 50 to 250 Ma with obliquity values from ~ 5° to ~ 65°. The geological evidence reported here supports orbital parameter scenarios where mean obliquity exceeds 45° during the Late Amazonian for a sufficiently long period to cause the observed ice accumulation and glacial flow. Tropical mountain glacier deposits have been documented in the equatorial regions of Mars [32,33] and glacial flow simulations [34] suggest significant atmospheric precipitation and accumulation. Furthermore, climate models [35] suggest that upwelling of water-rich air on the western flanks of Tharsis and the Tharsis Montes causes adiabatic cooling, snow precipitation and rapid accumulation sufficient to produce sustained snow and ice cover and glacial flow [34]. We hypothesize that similar conditions occurred in the Deuteronilus–Protonilus region (Fig 1) when, during periods of higher obliquity, water-rich polar air encountered the several-kilometer-high dichotomy boundary scarp, rose and underwent adiabatic cooling, causing snow precipitation, regional ice accumulation, and valley glacial systems here and elsewhere (e.g., [36]) along the dichotomy boundary at this latitude range.

The detailed preservation of textures typical of glacial surface and near-surface features (e.g., lineations, folds, craters) suggests that the current surface of this deposit is close to that of the original surface, and that downwasting due to the loss of ice from underneath a surface sublimation till has been retarded. This interpretation is supported by the topography of the deposit (Fig. 1) which indicates that the deposit is many hundreds of meters thick. These data suggest that the debris till overlying the glacier deposits may have severely retarded the sublimation rate of the ice beneath the till. Geological evidence for ancient ice (millions of years old) has been described in the Antarctic Dry Valleys [37]. If the lineated valley fill surface is indeed ancient and underlying ice is still preserved, this ice could provide a record of ancient climate change at latitudes readily accessible to future automated and human exploration.

Acknowledgments

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