MODIFICATION OF THE DICHOTOMY BOUNDARY ON MARS BY AMAZONIAN MID-LATITUDE REGIONAL GLACIATION.

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Introduction: One of the most topographically distinctive regions of the global dichotomy boundary extends to the highest northern latitudes (30-50°N), Deuteronilus-Protonilus Mensae (DPM), from ~290-360°W. This region, unlike most others along the boundary, is characterized by fretted terrain, in which the northern lowlands give way to progressively larger upland mesas and ultimately to sinuous valleys that extend into the adjacent highlands [1] (Fig. 1). The mesas are surrounded by lobate debris aprons (LDA), largely attributed to mass wasting aided by periodic flow of ice in pore spaces derived from diffusion of atmospheric water vapor [e.g., 2]. The fretted valleys are broad, steep-walled, flat-floored and extend deep into the uplands; they contain lineated valley fill (LVF). The similarity of mass wasting from the walls of the fretted valleys and the lobate debris aprons surrounding the mesas has led many to the conclusion that LVF may have formed largely by mass wasting [e.g., 3]. In Viking images, the lineated valley fill that occupies these valleys was shown to be characterized by axial lines (ridges and grooves) on the valley floors, and it was noted that these could be caused by convergence, in the middle of the valley, of linear debris aprons derived from opposite valley walls [e.g., 2]. On the other hand, Lucchitta [4] showed examples in which wall ridges and grooves bend downvalley to form axial lines, suggesting down-valley flow and a more important role for ice-related processes. In an update using MGS MOC and MOLA data, Carr [5] pointed out that the fretted valleys are poorly graded and concluded that they initially formed by fluvial processes similar to other valleys on Mars, but were subsequently widened and filled by the same mass wasting processes that formed the debris aprons; furthermore, Carr [5] observed down-valley topographic slope reversals leading him to conclude that down-valley flow of lineated valley fill was minor. Here we use new data from the Mars Observer, Odyssey, and Mars Express spacecraft to study the nature of the fretted valleys and the contained lineated valley fill to analyze their mode of formation and emplacement and their modification histories.

We completed a reconnaissance study of several dozen fretted valleys in this region and chose a typical example for detailed analysis at ~34°E, 41°N in the central region between Deuteronilus and Protonilus Mensae (Fig. 1). Using MOLA altimetry, and Viking, THEMIS, HRSC, and MOC images, we systematically analyzed the LVF from the narrow parts of the deeper upland valleys progressively toward the northern lowlands. In the most inland regions of the fretted valleys analyzed (areas A and B in Fig. 1b) the valleys are narrow (~10-20 km in width), often have distinctively cuspate (convex outward) shoulder-to-shoulder alcoves along the walls (region A) or larger tributary valleys often forming hanging valleys along the wall margins (region B). In contrast to the sharp parallel valley walls and parallel along-valley lineated fill typical of many fretted valleys described elsewhere [e.g., 2,3,5], these alcoves are sources of lineated valley fill (Fig. 1c) that can be seen to emerge from individual alcoves as lobes, descending onto the valley floor, bending and turning in a downslope direction, and merging with adjacent lobes,

deforming in the process ultimately to form the distinctive along-strike ridges of LVF. A particularly good example of the transport of material from an alcove and its deformation and inclusion into the main along-valley lineations (Fig. 1c) is seen as area C merges with the flow emerging from area B. Here, convex-outward, concentric-lobed flows are merging with adjacent lobes and converging with the along-valley flow, becoming progressively compressed and folded until they form the parallel along-valley lineations that are the hallmark of LVF. These types of alcoves, the arete-like borders between them, the arcuate-ridged lobes extending from them, the progressive compression and folding of the lobes as they converge onto the valley floor and lose their identity, are all hallmarks of glaciated valley landsystems on Earth [6,7]. In the context of such valley glacial environments, we interpret the alcoves on Mars to represent microenvironments where ice and snow accumulated, alcove walls shed debris onto the ice, and debris-covered glaciers emerged and moved downslope into the main valleys, widening the alcoves and creating aretes. We mapped the trends represented by the emergence of lobate material from these alcoves (Fig. 1b, narrow arrows) and the general trends with which they merge into the larger-scale LVF (wide arrows). The patterns in areas A, B, and C clearly indicate the convergence typical of glaciated valley landsystems [6,7] where abundant small debris-covered glaciers contribute to larger-scale valley glaciers. As the generally north-trending LVF emerges from areas A-C (Fig. 1b), the individual LVFs merge into two main trends, areas D and E. LVF C merges with B and continues ~95 km to the NNW where it bifurcates around a mesa to form LVF F and G, each continuing 50-75 km to the northern lowlands. Western portions of LVF B turn west into D, merging with LVF A to produce complex fold patterns. Portions of A turn NW and extend almost 100 km to the northern lowlands.

Several basic trends are observed over this region extending from A-B-C to the northern lowlands. First, valley widths in the north tend to be wider (up to a factor of 2-3) than in the southern regions. Valley wall alcoves are seen virtually throughout the system and continue to contribute material to the LVF through individual and adjacent lobate flows (Fig. 1c), even along the most distal large mesa. The distribution of the alcoves tends to be preferentially on north pole-facing slopes (Fig. 1b), but they occur with all orientations. The elevation of the LVF floor decreases by ~1500-2000 m from the proximal areas (areas A-C) to the end of the LVF in the northern lowlands. LVF slopes tilt toward the north, are less than 1° throughout most of the LVF floor, but increase rapidly to >1-2° in the northern 25-50 km of the LVF, adjacent to the lowlands. These latter areas are characterized by piedmont-like lobes extending into the northern lowlands between mesas. These latter features are very reminiscent of the fronts of terrestrial glaciers in terms of their lobate nature and relatively steep front, and in many cases are characterized by flow lines, pits and moraine-like ridges.

These general trends are accompanied by what appears to be a progressive fragmentation or "mesa-ization" of the extensive upland plateau. The large mesa between LVF areas A

and B (Fig. 1b) is barely connected to the plateau itself at its southern end, but to the north, widening of the valleys and enhancement of the alcoves has fragmented plateau segments into smaller and smaller mesas. Although the summits of the three mesas directly north of the plateau are the same, the size of the mesas has decreased substantially. This trend is consistent with the effects of the interpreted valley glaciation, in that the debris-covered glaciers in the alcoves along the margins erode progressively into walls, causing their retreat and widening over time. The lateral migration can form aretes and ultimately cut headward through narrow parts of the plateaus to form isolated mesas.

In summary, examination of new spacecraft data shows compelling evidence for an integrated picture of LVF formation, with a significant role being played by regional valley glaciation [e.g., 6,7] in the modification of the valley systems. We find evidence for: 1) localized alcoves, which are the sources of dozens of narrow, lobate concentric-ridged flows interpreted to be remnants of debris-covered glaciers; 2) depressions in many current alcoves, suggesting loss of material from relict ice-rich accumulation zones; 3) narrow pointed plateau ridge remnants between alcoves, similar to glacially eroded aretes; 4) horseshoe-shaped ridges up-valley and upslope of topographic obstacles.; 5) convergence and merging of LVF fabric in the down-valley direction, and deformation, distortion and folding of LVF in the vicinity of convergence, all consistent with glacial-like, down-valley flow; 6) pits and elongated troughs in LVF, particularly in areas where LVF is distorted, suggesting localized preferential sublimation of an ice-rich substrate lying below a rocky sublimation till; 7) distinctive lobe-shaped termini where the LVF emerges into the northern lowlands, with associated pitting; we interpret these to be the location of the relict glacial system margin. This assemblage of features can be traced and mapped in an integrated fashion (Fig. 1b) for over 200 km in length, and covers an area (~30,000 km^2) ~10 times that of the Antarctic Dry Valleys. The extensive development of lineated valley occurrences with very similar characteristics in fretted valleys in the DPM region suggests that glaciation may have been instrumental in the modification of the dichotomy boundary over an area as large as several million km^2. The age of the LVF in different parts of the DPM region has been estimated as Amazonian [e.g. 8,9]. The process of glaciation has clearly contributed to the erosion of the dichotomy boundary, broadening and extending valleys, and creating isolated mesas from glacial erosional activity, suggesting retreat over distances of many hundreds of kilometers.

References: [1] Sharp, R.P. (1973), *JGR., 78,* 4073. [2] Squyres, S.W. (1978), *Icarus, 34,* 600. [3] Carr, M.H. (1995), *JGR. 100,* 7479. [4] Lucchitta, B.K. (1984) *JGR., 89,* B409. [5] Carr, M.H. (2001), *JGR,* 23,571. [6] Eyles, N. (1983), The glaciated valley landsystem, in *Glacial Geology,* N. Eyles (ed.), pp. 91. [7] Benn, D.I., M.P. Kirkbride, L.A. Owen and V. Brazier (2003), Glaciated valley landsystems, in *Glacial Landsystems,* D.J.A. Evans (ed.), pp. 372. [8] McGill, G.E. (2000), *JGR, 105,* 6945. [9] Mangold, N. (2003) *JGR,* doi: 10.1029/2002JE001885.
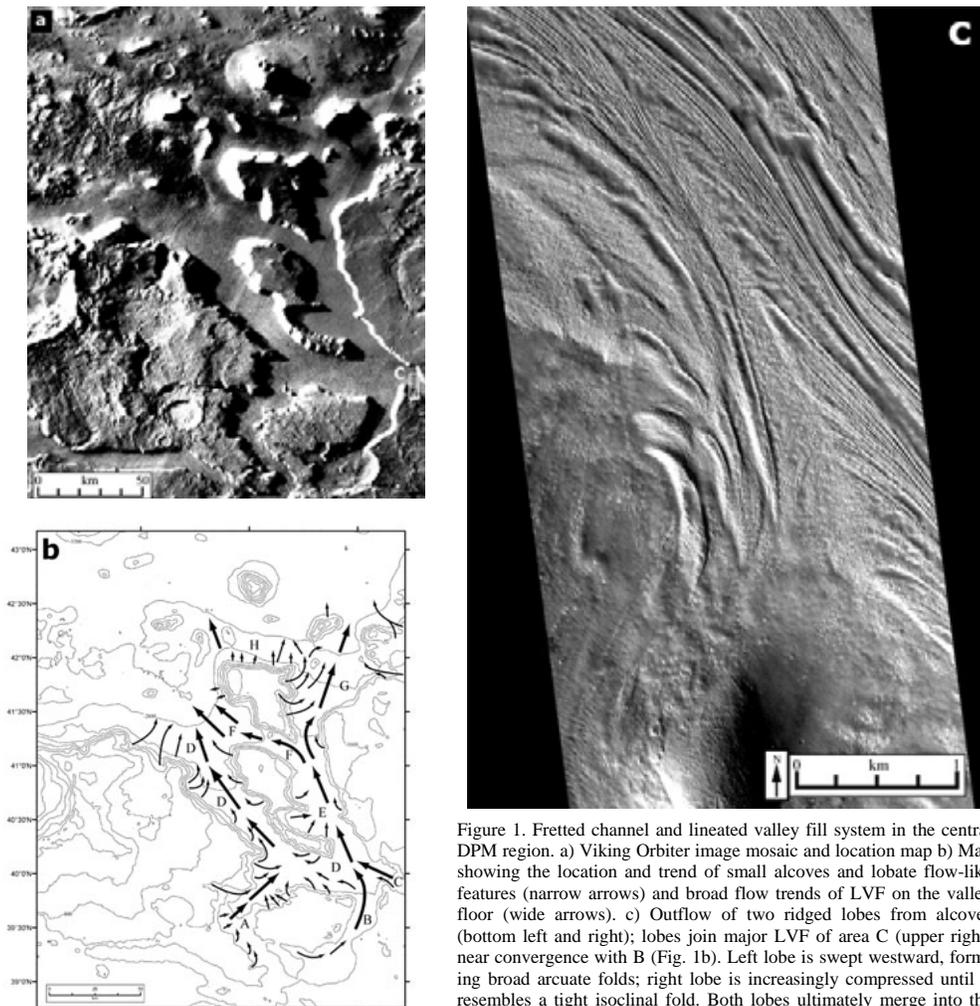
Figure 1. Fretted channel and lineated valley fill system in the central DPM region. a) Viking Orbiter image mosaic and location map b) Map showing the location and trend of small alcoves and lobate flow-like features (narrow arrows) and broad flow trends of LVF on the valley floor (wide arrows). c) Outflow of two ridged lobes from alcoves (bottom left and right); lobes join major LVF of area C (upper right) near convergence with B (Fig. 1b). Left lobe is swept westward, forming broad arcuate folds; right lobe is increasingly compressed until it resembles a tight isoclinal fold. Both lobes ultimately merge into the general LVF parallel to the valley walls. MOC R1702578.