Northern mid-latitude glaciation in the Late Amazonian period of Mars: Criteria for the recognition of debris-covered glacier and valley glacier landsystem deposits

James W. Head a,⁎, David R. Marchant b, James L. Dickson a, Ailish M. Kress a, David M. Baker a

⁎ Corresponding author.
E-mail addresses: james_head@brown.edu (J.W. Head), marchant@bu.edu (D.R. Marchant).

ABSTRACT

Lobate debris aprons (LDA) and lineated valley fill (LVF) have been known to characterize the mid-latitude regions of Mars since documented by Viking; their flow-like character suggested that deposition of ice in talus pile pore space caused lubrication and flow during an earlier climatic regime. A number of factors have remained uncertain, however, including the detailed structure and texture of LDA/LVF, the relationships between them, their direction of flow, the origin and abundance of the lubricating agent, and their exact mode of origin (e.g., ice-assisted rock creep, ice-rich landslides, rock glaciers, debris-covered glaciers). We use new High-Resolution Stereo Camera (HRSC) image and topography data, in conjunction with a range of other post-Viking data sets, and new insights provided by cold-based terrestrial glacial analogs, to assess the characteristics of LDA/LVF in the northern mid-latitudes of Mars. We find evidence that the characteristics and flow patterns of the LDA and LVF are most consistent with Late Amazonian debris-covered glacial valley landsystems. The broad distribution and integrated characteristics of the LDA/LVF systems suggest that earlier in the Amazonian, climatic conditions were such that significant snow and ice accumulated on mid-latitude plateaus and in valleys, producing integrated glacial landsystems, the remnants of which are preserved today beneath residual sublimation till derived from adjacent valley walls. Atmospheric general circulation models suggest that these climatic conditions occurred when Mars was at a spin-axis obliquity of ~35°, and the atmosphere was relatively dusty. Glacial flow modeling under these conditions produces patterns similar to those documented in the LDA/LVF, and SHARAD radar data suggests that significant amounts of ice remain sequestered below the sublimation lag today.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Mars is currently a cold, hyper-arid global desert (Baker, 2001); water is currently sequestered in the regolith-cryosphere, with the major surface reservoir residing in the extensive polar caps, and very small amounts in the atmosphere (Carr, 1996). Evidence is growing that in its past history, Mars has been characterized by significant variations in its spin-axis/orbital elements (obliquity, eccentricity and precession) (Laskar et al., 2004) and that these variations have led to the redistribution of water in the polar ice deposits to lower latitudes to create ice ages and their related deposits (e.g., Head et al., 2003). This has led to a renewed interest in the development of criteria to recognize non-polar ice-related, glacial and periglacial deposits that might represent the record of these excursions. Topographic and imaging data acquired by recent spacecraft have revolutionized our understanding of these deposits, providing detailed information that helps to characterize their key parameters (structure, morphology, slopes, elevations, morphometry, stratigraphic relationships, etc.) that are essential to interpreting these deposits. In particular, the High-Resolution Stereo Camera (HRSC) on board the Mars Express Spacecraft has provided image data and high-resolution digital elevation models (Neukum et al., 2004a,b; Gwinner et al., 2005; Scholten et al., 2005) that, together with complementary data from HiRISE, CTX, THEMIS and MOLA, have permitted the assessment of these types of features in the northern mid-latitudes of Mars.

Fretted terrain and fretted channels are very well developed in the northern part of Arabia Terra (Sharp, 1973) and were clearly identified in Viking data as the site of development of lobate debris aprons (LDA) (Fig. 1B) and lineated valley fill (LVF) (Fig. 1C) (Squyres, 1978, 1979). The detailed geological history and chronology of this region (McGill, 2000) provide a framework for the interpretation of modification processes operating on and near the dichotomy boundary. McGill (2000) underlines the conclusion that fretted channels and valleys formed early in Mars history (prior to middle Hesperian) and that the associated LDA and LVF represent Amazonian-aged modification of the fretted topography. Carr and Schaber (1977) analyzed the early Viking Orbiter images and concluded that frost creep and gelification were the primary processes in LDA formation. Squyres (1978) documented the fact that in the fretted terrain, debris aprons (LDA), characterized by sharply-defined flow fronts and convex-upward
surfaces, extend from massifs and escarpments outward to distance up to ~20 km. Squyres (1978, 1979) interpreted the aprons to have resulted from mass-wasted debris caused to flow by interstitial ice; he envisioned that during periods of climate change, atmospheric water vapor would diffuse into talus piles formed at the base of steep topography, and the resulting interstitial ice would cause mobilization and flow of the talus to produce lobes around isolated massifs. Longitudinal striae (ridges and grooves in surface debris) seen on the floors of the fretted valleys (LVF) were interpreted to be formed by ice-assisted debris aprons flowing from valley wall talus slopes and converging in the middle of the valley floor (Squyres, 1978, 1979). In the late 1970s a number of workers noted that some LVF in the Niliusyrtis region appeared consistent with down-valley flow (as reviewed by Baker (1982), p. 96–98). Following earlier ideas by Kochel and Baker (1981), Kochel and Peake (1984) provided detailed descriptions of geomorphological relationships and interpreted some debris aprons as formed by processes similar to those of terrestrial ice-cored or ice-cemented rock glaciers. Kochel and Peake (1984) further noted a transition from flow-parallel to flow-transverse ridge-and-furrow topography. Lucchitta (1984) interpreted the LDA and LVF as flow of debris with interstitial ice and showed evidence of local down-valley flow of LVF, likening some examples to flow patterns in glacial ice in Antarctica. Carr (1996; p. 116–120) urged caution in the general interpretation of a range of landforms as being due to glaciation (see Kargel and Strom, 1992; Kargel, 2004), on the basis of 1) the fact that the glacial hypotheses requires major climate change late in Mars history (e.g., Baker et al., 1991) for which he found little supporting evidence, and 2) that the low erosion rates in the Amazonian argues against any major climate excursions accompanied by precipitation, as envisioned by Baker (2001).

Pierce and Crown (2003) used new image and altimetry data to examine LDA in the Hellas region and found evidence for a wide range of possible ice content, interpreting the evidence to be consistent with multiple models of apron formation (e.g., rock glacier ice-assisted creep of talus, ice-rich landslides, debris-covered glaciers), with typical LDA resulting from flow of debris that was enriched in ground ice. Mangold (2003) presented evidence that ice content in LDA may exceed pore space, and Li et al. (2005) measured LDA MOLA profiles and compared these to simple plastic and viscous power law models for ice-rock mixtures; they concluded that LDA were ice-rich rock mixtures with some perhaps >40% ice by volume. Chuang and Crown (2005) documented the detailed character of sixty-five LDA in the Tempe Terra/Mareotis Fossae region and concluded that they consisted of mixtures of debris and ice, but that it was “difficult to constrain the internal distribution of ice or the method of debris apron initiation from the current datasets.” In summary, all workers agree
that the formation of LDA and LVF involves both talus and ice, but there is disagreement as to the amount of ice: One end-member calls on formation by ice-assisted creep of talus (often defined as producing a “rock glacier”) (e.g., Squyres, 1978, 1979), while another end-member calls on formation as debris-covered glaciers, (predominantly glacial ice with a cover of sublimation lag or till) (e.g., Head et al., 2006a,b). Here we develop criteria to distinguish between these end-members and investigate a wide range of occurrences to assess the origin of LDA and LVF.

Although temperate glacial and periglacial climates and analogs can offer insight into these environments, the extremely cold and hyper-arid conditions on Mars are more likely to be related to environments in which cold-based glaciation is the dominant process and temperatures are virtually always below the freezing point of water (e.g., Marchant and Head, 2007). Terrestrial cold-based glacial analogs have recently been applied to the analysis of fan-shaped deposits on the NW flanks of the Tharsis Montes and Olympus Mons, and have been interpreted to represent extensive tropical mountain glaciers formed by enhanced snow and ice deposition during periods of high obliquity in the Amazonian (Williams, 1978; Lucchitta, 1978; Head and Marchant, 2003; Neukum et al., 2004a,b; Shean et al., 2005, 2007; Head et al., 2005; Miljkovic et al., 2006; Forget et al., 2006; Kadish et al., 2008).

Additional Earth glacial analogs have been used to develop criteria for the recognition of glacial deposits in various topographic and environmental settings on Mars (Marchant and Head, 2006). These criteria have recently been applied to the assessment of the fretted terrain, one of the hallmark morphologies of the highland–lowland boundary region in the northern mid-latitude Deuteronisus–Protonilus Mensae area (30°–50° N and 10°–75° E) (Fig. 1). An increasing awareness of the possible role of glacial deposits on Mars (e.g., Lucchitta, 1981, 1984; Head and Marchant, 2003; Marchant and Head, 2007) led to the investigation of the question of whether the accumulation of snow and ice, and resulting glacial activity, could account for some of the observed characteristics of the LDA and LVF in the fretted terrain. In one area analyzed (Fig. 1, point 1) (~37.5° N, 24.2° E) (Head et al., 2006a) evidence was presented that lineated valley fill formed in multiple accumulation zones in breached craters, alcoves, and tributary valleys and flowed laterally down-valley forming a major trunk system that was characterized by compression of ridges at constrictions, tight folds at converging branches, and a lobate, convex-upward terminus. In a second area (Fig. 1, point 2) (~40.5° N, 34.5° E) (Head et al., 2006b), a single integrated glacial flow system was documented covering ~30,000 km² and consisting of multiple, theater-headed, alcove-like accumulation areas, converging patterns of downslope flow into several major valley systems, and broad piedmont-like lobes where the LVF extended out into the adjacent lowlands. The features and deposits in these two areas were interpreted to represent intermontaine valley glacial systems dating from earlier in the Amazonian.

An additional detailed morphological analysis of a 70,000 km² region just east of the area treated by Head et al. (2006b) (north-central Deuteronisus Mensae, south of Lyot, in the vicinity of Sinton Crater; Fig. 1, point 5) was described by Morgan et al. (2009), and is characterized by the distinctive sinuous ~2 km-high plateau scarps, abruptly massifs to the north, and extensive fretted valleys dissecting the plateau to the south. These features are modified by processes that form LVF in the fretted valleys, and LDA along the dichotomy scarp and surrounding the outlying massifs. High-resolution HRSC image and topography data show that LVF and LDA deposits are comprised of the same material, show integrated flow patterns, and originate as debris-covered valley glaciers; the proportion of ice and debris involved is high and a significant amount of ice (hundreds of meters) is likely to remain today beneath a thin cover of sublimation till. There is depositional evidence to suggest glacial highstands at least 800 m above the present level, implying previous conditions in which the distribution of ice was much more widespread. In Nilosyrtis Mensae, farther east along the dichotomy boundary (Fig. 1, points 9, 10), LVF and LDA show stratigraphic, topographic, and textural relationships that indicate extensive glaciation along the boundary and multiple phases of glacial overprinting during the late Amazonian (Leyvi et al., 2007). Evidence was analyzed and presented for the regional integration and flow of LVF material and its interpretation in the context of cold-based glaciation in the Antarctic Dry Valleys.

The synthesis of these areas led to several additional questions: 1) What was the original thickness of the glacier ice? 2) How much ice-surface lowering, through sublimation, retreat and ice loss, has occurred to bring the LDA and LVF surfaces to their presently observed levels? 3) Have there been multiple periods of glaciation, and if so, over what time periods? Preliminary analyses (e.g., Marchant and Head, 2008) suggested that the LDA and LVF might be parts of a larger phase of glaciation, during which glacial ice was much thicker and perhaps completely filled the valleys. Dickson et al. (2008) described evidence for glacial thickness maxima and multiple glacial phases in the Coloe Fossae region of the dichotomy boundary (Fig. 1, point 7). They documented the topography associated with a sloping lobe interpreted to be evidence of a glacial highstand that was part of a LVF glacial landsystem. The elevation difference between the upper limit and the current surface of the LVF at the study site is ~920 m and Dickson et al. (2008) interpreted this difference to reflect the minimum amount of ice-surface lowering of the valley glacier system during downwasting and retreat. Consistent with a general lowering of the ice surface are multiple moraines and/or trimlines, and changes in LVF flow patterns, including local flow reversals, as the ice retreated and decreased in thickness. Furthermore, the clear superposition of several lobes out onto the current surface of the LVF indicates that a smaller-scale phase of glaciation followed the lowering of the valley glacial landsystem. These data suggest that the major Late Amazonian glaciation that produced LVF in this region involved significantly larger amounts of ice than previously thought, and that subsequent, less extensive glaciation followed (Dickson et al., 2008).

2. Synthesis of criteria for recognition

On the basis of these studies and using a range of terrestrial analogs most likely to apply to the recent cold-desert environment of Mars (e.g., Marchant and Head, 2006, 2007), the following criteria have been developed to assist in the identification of debris-covered glacial-related terrains on Mars. We first list the features (Fig. 2), followed by the interpretation of each, listed in parentheses: 1) alcoves, theater-shaped indentations in valley and massif walls (local snow and ice accumulation zones and sources of rock debris cover) (Fig. 2A), 2) parallel arcuate ridges facing outward from these alcoves and extending downslope as lobe-like features (flow-deformed ridges of debris) (Fig. 2B), 3) shallow depressions between these ridges and the alcove walls (zones originally rich in snow and ice, which subsequently sublimated, leaving a depression) (Fig. 2B, C), 4) progressive tightening and folding of parallel arcuate ridges where abutting adjacent lobes or topographic obstacles (constrained debris-covered glacial flow) (Fig. 2B, C), 5) progressive opening and broadening of arcuate ridges where there are no topographic obstacles (unobstructed flow of debris-covered ice) (Fig. 2B, C), 6) circular to elongate pits in lobes (sublimation of surface and near-surface ice) (Fig. 2B, C), 7) larger tributary valleys containing LVF formed from convergence of flow from individual alcoves (merging of individual lobes into LVF) (Fig. 2A, 8) individual LVF tributary valleys converging into larger LVF trunk valleys (local valley debris-covered glaciers merging into larger intermontaine glacial systems) (Fig. 2A), 9) sequential deformation of broad lobes into tighter folds, chevron folds, and finally into lineated valley fill (progressive glacial flow and deformation) (Fig. 2B, C), 10) complex folds in LVF where tributaries join trunk systems (differential flow velocities causing folding) (Fig. 2B, C), 11) horseshoe-like flow lineations draped around massifs in valleys and that open in a downslope direction (differential glacial
flow around obstacles) (Fig. 2A), 12) broadly undulating along-valley topography, including local valley floor highs where LVF flow is oriented in different down-valley directions (local flow divides where flow is directed away from individual centers of accumulation) (Fig. 2A), 13) integrated LVF flow systems extending for tens to hundreds of kilometers (intermontaine glacial systems) (Fig. 2A), and 14) rounded valley wall corners where flow converges downstream, and narrow arete-like plateau remnants between LVF valleys (both interpreted to be due to valley glacial streamlining) (Fig. 2A).

Taken together, the occurrence of these types of features is interpreted to represent the former presence of debris-covered glaciers and valley glacial systems in the Deuteronilus–Protonilus region (e.g., Head et al., 2006a,b). Snow and ice accumulating in alcoves, together with rock debris shed from adjacent steep walls, created debris-covered glaciers that flowed downslope, merging with other ice lobes to form ever-larger LVF glacial systems. Using these criteria, we now explore other parts of the mid-latitudes (Fig. 1) to assess evidence for similar features and processes.

3. Application of the criteria to other parts of the Deuteronilus–Protonilus region

Squyres (1978) showed that locations of LDA and LVF were concentrated in a distinct mid-latitude band, suggesting a climate control on their origin. We have applied the criteria for glacial deposits outlined above to detailed analyses of several additional areas in this northern mid-latitude region (Fig. 1), and we report a summary of our findings here. Although evidence has been presented for a debris-covered glacier origin for some occurrences of the LDA and LVF, a number of factors have remained uncertain, including: 1) determining the direction of flow in LDA and LVF, either normal to the valley (Squyres, 1978), or possibly parallel (down-valley) (Lucchitta 1984); 2) understanding of the detailed structure and texture of the LDA; 3) understanding of the relationships between the LDA and the LVF; 4) establishing the relationship of LDA and LVF to adjacent walls; 5) providing evidence for the origin of the lubricating agent and flow mechanism; 6) distinguishing the mode or modes of origin of the LDA

Fig. 2. A. Synoptic High-Resolution Stereo Camera (HRSC) image data superposed on HRSC DTM, with HRSC stereo-derived, color-coded topography and topographic contours displayed. This product is typical of those used in this study and is essential in showing the detailed relationships between topographic and morphologic features, particularly for determining E–W-oriented slope measurements where MOLA groundtracks are widely spaced. Northern Arabia Terra region (24° E, 39° N; Fig. 1, point 1). Numbers here, and in B and C show the types of features described in the text as criteria for recognition of glacial deposits. Inset box shows location of B. Contour interval is 250 m. Portion of HRSC images 1483_0000. B. Degraded impact crater and LDA and LVF. Accumulation of LDA along the crater walls has led to flow toward the breach in the crater rim, and out into the surrounding valley, where the flow joins LVF from the alcove to the east, resulting in complex patterns of folding and deformation. Location is shown by box in A. Portion of HRSC image 1201_0000. C. LDA at the edge of the dichotomy boundary converging northward downslope to form LVF; note that the LDA appear to emerge from the top of the plateau, suggesting the present of a plateau icefield feeding the valley glacial landsystem. The lobes are seen to transition form arcuate, outward-facing shapes, to chevron shaped, and then to compress further and merge into LVF. THEMIS V09872024 draped on MOLA; VE = 5×. Scene is ~16 km across at the crest of the slope face.
and LVF (e.g., ice-assisted rock creep, ice-rich landslides, rock glaciers, debris-covered glaciers); and 7) assessing the implications for the geological history of Mars. We address these questions in an analysis of several regions in the northern mid-latitudes.

3.1. North-Central Arabia Terra (Fig. 1, location 3; Fig. 3)

Regional analyses of LVF in the southern part of this area (Head et al., 2006a) have shown evidence for local sources of LVF in alcoves in valley walls, down-valley flow, merging of flowlines into broad trunk valleys, extensive along-valley flow, and termination in lobate deposits, all features that are similar to valley glacial landsystems on Earth (Boulton and Eyles, 1979; Eyles, 1983; Benn et al., 2003). In this preliminary analysis we mapped a ~50,000 km² area (Fig. 3) just north of the area of LVF interpreted to be a valley glacial landsystem (Head et al., 2006a). We found it useful to subdivide LDA into linear (occurring along valley walls and crater interiors) and circumferential (aprons generally surrounding isolated massifs) (Fig. 3A).

Fig. 3. Northern Arabia Terra (Fig. 1): A. Topographic contour map of study region: 100 m contour interval. Arrows show mapped directions of flow. Boxes show locations of Figs. B–F. B. Massif with circumferential LDA, Themis V13879005 with Viking inset for comparison. C. Linear LDA along crater wall. Note alcoves, lobes, and divergence around obstacle. Themis V10834007. D. Large fold where LVF converges and becomes LDA, Themis V11433004. E. Massif LDA meet and flow laterally from a divide, forming LVF. Themis V14216012. F. Linear LDA blocked by parallel ridges, merges to form LVF and piedmont lobe in gap. Themis V12057009.
3.1. Direction of flow in LVF

In the mapped region, flow directions are away from the massif walls in circumferential LDA (Fig. 3A, B) and away from valley and crater walls in linear LDA (Fig. 3C); however, when massif/wall LDA/LVF meet in central valley floors (Fig. 3D) or between massifs (Fig. 3E) it merges and commonly follows the local topographic gradient to create along-valley flow, forming complex folds and other deformation patterns (Fig. 3D). In some places, flow divides can be established where flow patterns diverge from a local high and extend down-valley in opposite directions (Fig. 3E, middle; Fig. 3D, lower right).

3.1.2. Detailed structure of LDA

New high-resolution THEMIS, MOC and HRSC data show much more detail than Viking (Fig. 3B) and reveal that aprons are composed of multiple individual lobes derived from local indentations (alcoves) in the massif (Fig. 3B) and valley walls (Fig. 3C); pitting suggests loss of ice by sublimation and marginal ridges are reminiscent of moraines. Localized convex-outward ridges in the proximal parts of the aprons (Fig. 3B, C) are similar to ridges on debris-covered glaciers (Levy et al., 2006; Marchant et al., 2007).

3.1.3. Relationships between LDA and LVF

Where massifs face outward to plains (Fig. 3B), debris aprons spread out as lobes from alcoves and deform in relation to their neighbors; where they meet obstacles, they compress and flow around the obstacles (Fig. 3C), and in some cases, where the obstacle is parallel to the crater wall, they converge and flow through a low point in the obstacle to create a piedmont-like lobe (Fig. 3F) and local LVF. Where massifs are close together, LDA converge in the middle of the valley, turn and flow laterally, often forming divides (Fig. 3E). In some cases (Fig. 3D), LVF flows from two different valleys, converging, incorporating a LDA from the southern valley wall, and forms a huge broad fold more than 25 km in length that becomes part of the linear LDA in the southern part of the valley wall (Fig. 3A). Thus, at least in these numerous cases, LDA becomes LVF and vice versa.

3.1.4. Relationship of LDA/LVF to adjacent walls and origin of the lubricating agent

Numerous local alcoves appear to be the source of the concentric outward ridges that are the hallmarks of the LDA deposits (Fig. 3A–C, E–F); these are very similar to the debris-covered glacier source alcoves seen in the two regions interpreted to represent integrated valley glacial land-systems (Head et al., 2006a,b). Detailed HRSC topography often shows evidence for depressions at the head of the ridges and the base of the massifs, suggesting that ice and snow once accumulated there to form debris-covered glaciers, but since has sublimated.

3.2. Mamers Valles (Fig. 2, location 4; Fig. 4)

Analysis of MOLA data in this area (Carr, 2001) revealed slope reversals in Mamers Valles, a Hesperian fretted valley, suggesting that down-valley flow of lineated terrain was minor. LDA were interpreted by Carr (2001) as debris flows lubricated by ground ice in material undergoing wall-slope-related mass wasting. In this area we analyzed LDA, LVF, and their relationships along >900 km² of the length of Mamers Valles from the crater Cerulli north to the area just south of Deuteronilus Colles (Fig. 1, location 4), and also assessed its distribution in along-valley and intersecting craters (Fig. 4).

Mamers Valles can be subdivided into its lower reaches, where it averages ~10 km in width, and its upper reaches where it is 20–30 km in width (Fig. 4A). The upper reaches are characterized by linear LDA; high-resolution images show that LDA are composed of dozens of parallel lobes that originate in alcoves in valley walls and extend onto the valley floor, creating a marginal ridge, and abutting similar parallel lobes emerging from the opposite wall (Fig. 4B). LDA can also emerge from theater-like remnant crater rims (Fig. 4B) and from tributary valleys intersecting the main valley wall (Fig. 4C); the tributaries are commonly characterized by LVF that merges with the LDA, producing a larger than average lobe and/or unusual pitted surface texture (Fig. 4C). Asymmetry in LDA development is commonly observed, with south-facing LDA more extensive. In narrower areas of the valley floor, lobes from opposite sides meet and their distal ridges form parallel linear ridges (Fig. 4B); in wider areas, LDA do not meet (Fig. 4C), and unusual surface textures and features suggestive of ice-related periglacial processes are observed (Fig. 4C, D), including lobe-shaped depressions trending in the same direction as the LDA lobes (arrows in Fig. 4D). Where some LDA meet in the central part of the valley, they are distorted along-valley (Fig. 4E) in a common flow direction, become complexly folded (north part of Fig. 4E) and begin to merge into LVF. In some cases (Fig. 4F) LDA derived from wall alcoves rapidly deform, lose their individual identity and merge into LVF. In the much narrower southern part of Mamers Valles (Fig. 4A), LVF forms in the narrow tributaries from coalescing alerce-fed flow and emerges into the main channel (Fig. 4G), where it joins other tributary-fed LVF and linear channel-wall LDA, compressing and deforming to produce ever-narrower folds until it becomes LVF. The unusual nature of superposed impact craters (Fig. 4B, D) suggests that the substrate contained significant ice (e.g., Kress and Head, 2008) and that deformation has been minimal since its emplacement (Carr, 2001). Along-valley slope reversals (Carr, 2001) are caused by local divides, where flow is away from broad accumulations in different directions (Fig. 4A). Where narrow, along-valley integrated LVF flow opens into a significantly larger part of the valley (such as a large depression; Fig. 4A) the distinctive along-valley flow terminates in a broad piedmont-like lobe (Fig. 4H), further contributing to the along-valley variations in topography described by Carr (2001).

3.2.1. Direction of flow in LVF

LVF flow direction is normal to valley walls where valleys are wide and LDA from opposite walls are separated (Fig. 4C) or simply abut (Fig. 4B).

3.2.2. Relationships between the LDA and LVF

Where LDA meet and begin to merge, LDA flow direction is distorted down-gradient (Fig. 4E); continued merging causes LDA to compress (Fig. 4E, G), lose their individual identity (Fig. 4F), and merge into and become true LVF (Fig. 4F–H).

3.2.3. Direction of flow in LVF

As noted by Carr (2001), topographic gradients are variable along-valley; these topographic slope reversals commonly reflect observed variations in LDA/LVF flow directions derived from detailed analysis of folds and deformed surface textures (Fig. 4A). Along-valley slope reversals tend to occur at flow divides, and distinctive slope changes occur where LVF empties into wider depressions (Fig. 4H).

3.3. Ismeniae Fossae region (Fig. 1, location 6; Fig. 5)

In this area we analyzed LDA surrounding several isolated mesas adjacent to the dichotomy boundary in the area (41° E, 45° N) north of Ismeniae Fossae, the northernmost part of the dichotomy boundary. The region is characterized by two major mesas and a series of smaller satellite mesas and hills with surrounding LDA. The current mesa topography is characterized by a series of bite-like 5–10 km wide alcoves along their margins (Fig. 5A). In contrast to the broadly lobate nature of LDA seen in Viking images, linear lobate debris aprons along the dichotomy boundary scarp (Fig. 5A) are composed of numerous parallel ridged lobes (Fig. 5B) emerging from alcoves in the scarp wall (Fig. 5G) and flowing downslope, compressing and deforming to form the broad apron seen at Viking resolution. Distal, medial, and looping concentric ridges are common, as are pits and depressions (Fig. 5B). Where downslope obstacles are encountered (Fig. 5G) flowlines are
diverted and sometimes join with LDA from other adjacent mesas. In
the circumferential LDA surrounding the mesas, similar relationships
are observed (Fig. 5C); here two major LDA lobes source in alcoves as a
series of small lobes that join together into larger lobes, extending
down to the base of the LDA. Many additional smaller lobes source in
smaller alcoves between these two and bend around the major
obstacle and rejoin distally to form portions of the broad distal LDA.

West of this area (Fig. 5A), circumferential LDA again are composed of
numerous individual lobes sourcing in alcoves of various sizes (Fig.
5D), flowing downslope as discrete, but conjoined lobes, and flowing
around obstacles (lower right) toward the adjacent lowlands (lower
left); the 4 km wide alcove in the top middle displays at least two
generations of lobes (one which extends to the distal reaches of the
LDA, and two smaller, apparently superposed lobes confined to the
vicinity of the alcove). LDA extending out onto adjacent lowland floors terminate in steeper-sloped, outward-facing scarps (Fig. 5D), series of parallel ridges reminiscent of moraines (Fig. 5B), pitted and grooved textures (Fig. 5B–E), and where they encounter local depressions, piedmont-like flow lobes (Fig. 5E). Where mesas are closely spaced (Fig. 5F), LDA merge and are diverted laterally into broad folds that are
Fig. 7. Acheron Fossae region, north of Olympus Mons (Fig. 1): A. MOLA gradient map of eastern Acheron Fossae with color-coded topography. Boxes show locations of panels B–G. Arrow opens toward perspective view in E. B. Graben, LVF and LDA. Arrow opens toward perspective view in D, and line shows profile location in C; HRSC 0037. C. MOLA altimetric profile (orbit 13424) across B. D. Perspective view of crater in B; arrow in B shows viewing perspective. HRSC 0037 draped on MOLA. VE = 2×. E. Perspective view of piedmont-like LDA emerging from Acheron Fossae graben. Arrow in A opens toward perspective view. THEMIS V09791029 and V01852010 draped on MOLA. VE = 2×. F. Impact crater with LDA on southern wall and floor; HRSC 0037. G. Impact crater with LDA on southern wall and floor; HRSC 0037.
compressed and merge into LVF, flowing downslope to become broad distal lobes; in this region, there is a topographic and flow divide separating north- and south-flowing LDA and LVF. Evidence for an apparently superposed LDA with abundant ridges and a distal moraine-like feature is seen emerging from an alcove in the middle right (Fig. 5F). In other cases where mesas are close together (Fig. 5H), flow lines emerging from alcoves rapidly bend downslope and join other alcove and valley tributaries, compressing and deforming to create LVF.

Our analysis suggests that linear LDA and LVF are intimately related in morphology and modes of origin. The very close relationship of LDA source regions with alcoves (Fig. 5B, D, G), and the wide range of associated features (e.g., concentric ridges (Fig. 5B, G), pits (Fig. 5B–E), moraine-like features (Fig. 5B, D), piedmont-like lobes (Fig. 5E), merging of flowlines into LVF (Fig. 5F, H), etc.) all suggest an integrated system, beginning in alcoves and ending in distal lobes. We thus interpret the evidence documented here to support a major role for debris-covered glaciers. As LDA grew and coalesced (Fig. 5B–E, G), they merged between massifs and began to flow down-gradient, forming LVF (Fig. 5F, H), ultimately creating valley glaciers with divides (Fig. 5F, H) and integrated glacial landsystems (e.g., Head et al., 2006a,b) (Fig. 5A).

3.4. Coloe Fossae region (Fig. 1, location 7; Fig. 6)

A distinctive region along and just south of the dichotomy boundary is characterized by a series of narrow linear graben extending for about 200 km NW-SE (Fig. 1, point 7) (Coloe Fossae; 36°–42° N 53.5°–58° E). We compared the LDA and LVF found here with areas characterized by mesas (Ismeniae) and broad sinuous valleys (Mamers) of the fretted terrain, and to Acheron Fossae, an area of LDA/LVF development outside northern Arabia Terra. The scarp defining the main dichotomy boundary, and the mesas that extend to the north, are both characterized by classic examples of LDA. Along the scarp, LDA, seen at Viking resolution to be broad aprons, are revealed to be characterized by multiple individual lobes (Fig. 6B, top; Fig. 6C, bottom) extending 5–7 km from scarps into the surrounding plains; characteristics include proximal radial ridges, distal concentric ridges, and irregular pits and depressions (Fig. 6B, C). In some cases (Fig. 6B, bottom) there is clear evidence of a younger, smaller set of lobes extending 3–4 km out on top of the broader 10–12 km lobes. Along the north–south portion of the scarp (Fig. 6A, F) LDA extend from the scarp about 16 km out into the adjacent lowlands; here there is evidence for extensive pits and irregular depressions, often following the radial and concentric ridged texture. Similar relationships are seen along the mesas that characterize Protonilus Mensae, the region in front of the scarp. LDA are formed of multiple individual lobes distinctly related to alcoves (Fig. 6D) with radial, concentric and pitted textures, with small-scale pitting particularly abundant on the distal margins. More than one generation of lobe formation is also suggested by the stratigraphic relationships with a smaller (4–6 km) more distinctive set of lobes extending out over the larger more extensive (16–18 km) lobes (Fig. 6D). At some mesas (Fig. 6E), LDA are deflected around massifs and join LDA that are forming from the mesa itself. Portions of the proximal parts of these two peripheral lobes (Fig. 6E, bottom) are similar to LVF textures; in addition, LDA extending downslope from the eastern part of the mesa are being deformed into folds and incorporated into the along-valley flow of the broad lobe (Fig. 6E lower right). Within the graben of Coloe Fossae, the surface texture is much more linear and wavy (Fig. 6H) than that typical of the more lobate LDA surrounding mesas and more similar to LVF. Similar relationships are seen in Acheron Fossae (described below), where viscous-flow floor texture in flat, straight-walled graben form typical linear LDA, due to the fact that local alcoves are minimized in the straight graben wall. This linear LDA texture forms from LDA converging from the walls and meeting in the center; as at Acheron, where slopes steepen, the linear LDA can flow down-valley, often forming distal lobes. The waviness in the lineated valley fill (Fig. 6) can often be related to small irregularities in the graben walls. Central structures in the lineated LDA include broad folds, some of which appear to be breached, forming axial depressions (Fig. 6H, arrows; compare to Fig. 6E).

In cases where scarp and mesas are close in proximity, LDA forming on opposite slopes rapidly merge and form LVF (Fig. 6B, bottom). LDA formed in a topographically constrained area such as a sloping impact crater interior (Fig. 6F, bottom) show evidence of compression against the distal rim of the crater, diversion to the North, and flow out into the surrounding region to form an LVF-like texture. The linear LDA on the floor of Coloe Fossae (Fig. 6H) are testimony to the fact that LVF can originate from valley walls and form LVF-like textures.

3.5. Acheron Fossae region (Fig. 1, location 14; Fig. 7)

LVF and LDA of glacial origin are common in association with the graben and massifs (Fig. 7). Acheron Fossae are a series of arcuate parallel graben on a rise north of Olympus Mons (217°–237° E; 34°–40° N). The graben floors are characterized by viscous-flow-like features (Kronberg et al., 2006) resembling LDA and LVF. We analyzed the floors and walls of the graben composing Acheron Fossae, examining the viscous-flow-like features there and assessing their morphology, topography, relation to underlying topography, slope and orientation. We also compared the graben floor structures to lobate deposits found on the pole-facing slopes of impact craters superposed on the Acheron Fossae region (Fig. 7A). Three types of viscous-flow features are seen in the Acheron region and differ somewhat from the classic LDA and LVF in Deuteromilus Mensae (Squyres, 1979); we focus on the eastern half of Acheron (Fig. 7A) to illustrate these:

1) Linear LDA: Distinctive lobate features are observed on the graben floor (Fig. 7B). The ridged texture of these features is generally parallel to the graben walls and is somewhat sinuous but does not commonly form the discrete fold-like lobes typical of many LDA (Squyres, 1979; Lucchitta, 1984; Pierce and Crown, 2003; Head et al., 2006). The reason for this appears to be the distinctly straight linear walls of the graben, which do not form the alcoves that are common on sinuous valleys and their tributaries in the Deuteromilus region (Figs. 3–6); in these areas alcoves appear to serve as distinctive accumulations zones for snow, ice and rockfall, and thus are the emergent point of the lobes forming the individual folds within the broader LDA. Do the linear LDA show significant lateral movement? Fig. 7B–D shows a 7–8 km diameter impact crater on the floor and rim of an ~8 km wide graben; here, in the perspective view (Fig. 7D), the linear LDA form on the north-facing graben wall and extend across the floor, over the rim, and down into the impact crater over a distance of ~6–7 km. There is also evidence that linear lobate debris aprons are forming on the south-facing slopes, although they tend to be less prominent. The nature of the lineal LDA developed on the floors of Acheron Fossae.
is much more similar to these developed in graben locally along the dichotomy boundary in the Deuteronis–Protonilus region (e.g., Coloe Fossae; Fig. 6) than along the boundary scarp or in channels and crater walls there (Head et al., 2006a,b; Figs. 3–6).

2) Lineated valley fill and piedmont-like deposits: In environments in Acheron where slopes increase, such as in the dome-like structure at the eastern end, structures and morphologies differ. Here, linear debris aprons are developed in the graben but rapidly turn and flow downslope to create lineated valley fill and, where the graben open to the surrounding plains, large piedmont-like lobes (Fig. 7A, E). In this perspective view, the large piedmont-like lobate debris apron emerges from the graben, flows around an obstacle, and spreads out into a large lobe about 30 km wide. A similar fan is formed just to the north, from flow emerging from the wide graben there (Fig. 7A). Thus, in these cases, linear LDA produce LVF which in turn forms large lobes as the LVF flows downslope and out onto the surrounding plains.

3) Post-Acheron Impact Craters: In this environment, numerous post-Acheron impact craters show evidence of the same type of lobate fill (Fig. 7F, G) as seen in the crater on the floor and wall of the graben (Fig. 7B, D). The northern parts of these craters show interior wall and floor textures (central uplifts, wall terraces, floor roughness) typical of relatively fresh impact craters. The southern walls and floor, however, are almost completely obscured by a darker smoother material forming lobate deposits extending from the inner wall down on to the crater floor. In detail, the deposits are characterized by the same lobate ridged texture seen elsewhere in LDA; the lobes also follow local topography on the crater floor (Fig. 7F, G).

3.5.1. Range of environments in which LDA occur

These occurrences broaden the longitude range in which northern mid-latitude LDA and LVF are observed extending the range sufficiently to suggest that the deposits may be common globally at other similar longitudes (Fig. 1; Squyres, 1979), and thus may be related to broad climate latitudinal change rather than specific conditions related to the dichotomy boundary scarp. These occurrences also broaden the geological setting to include additional linear graben (see also Coloe Fossae, Fig. 6) and emphasize the importance of occurrence inside superposed impact craters, and north-facing slopes.

3.6. Assessment of other regions in the 30°–50° N latitude range

The presence of valley glaciers could be due to local environmental conditions in which the accumulation of snow and ice was favored (e.g., Hecht, 2002). The widespread distribution of these glacial systems in the Deuteronis–Protonilus highland region (Fig. 1), however, suggests that conditions were much more regional, extending across a significant latitude band. To address the question of whether climatic conditions conducive to glacial activity extended beyond the Deuteronis–Protonilus region, we undertook a broad review of the remaining longitudes at these latitudes and found abundant evidence of local and regional Amazonian glacial deposits in the following areas (Fig. 1, including: 1) Elysium Rise: Hecates Tholus (Fig. 1, point 11): A 45 km wide depression at the base of Hecates Tholus is host to a series of debris-covered glacial deposits (Hauber et al., 2005). 2) Phlegra Montes (Fig. 1, point 12): Debris-covered glacial deposits are located along the scarps of the montes as well as surrounding individual massifs there (e.g., 30°–50° N, 160°–167° E) (Safaeinili et al., 2009). Craters with concentric crater fill show evidence of the former presence of significant thicknesses of ice (overlapping crater rims) in this region (e.g., Dickson et al., submitted for publication). 3) Arcadia Planitia (Fig. 1, point 13): Degraded mountains in central Arcadia contain LDA-LVF deposits (e.g., 35°–40°N, 185°–190° E). 4) Tempe Terra Region (Fig. 1, point 15): LVF and LDA of apparent glacial origin occur in numerous places in the graben and mountains in this region (e.g., 45°–52° N, 280°–300° E) (van Gasselt et al., 2002; Chuang and Crown, 2005). 4) Instances have also been reported of remnant LDA-like features formed of ice at even lower latitudes (Hauber et al., 2008).

4. Discussion and conclusions

The following characteristics are typical of lobate debris aprons and lineated valley fill: 1) Lobate debris aprons (LDA) can be subdivided into linear (along-valley walls and degraded crater walls) and circumferential (around isolated massifs); 2) LDA commonly form from numerous parallel individual flow lobes emanating from alcove-like indentations in massif and valley walls; 3) in some cases LVF glacial systems clearly merge with linear LDA; 4) in some cases linear LDA derived from opposite valley walls merge and flow down-valley; 5) in massif clusters, circumferential LDA often meet those from adjacent massifs, merge, and then flow downslope, forming piedmont-like lobate terminations in the adjacent lowlands.

The relationships described and shown in Figs. 2–7 suggest that linear LDA and LVF are intimately related in morphology and modes of origin. Evidence of melting associated with LDA and LVF in the Arabia Terra region is extremely rare, but in one location in this region (Fig. 6G), several small channels are seen draining from the front of LDA; the unusually abundant pitting in the LDA here and the frontal pits at the location of the small channels suggests that a significant component of ice was involved in the formation of these deposits (e.g., Pierce and Crown, 2003; Mangold, 2003; Li et al., 2005). Among the hypotheses outlined above for the origin of LDA and LVF (e.g., groundwater-fed mobilization, ice-assisted rock creep, ice-rich landslides, rock glaciers, and debris-covered glaciers), we interpret the evidence documented here to support a major role for debris-covered glaciers. Formation of LDA by accumulation of snow and ice in alcoves, and in tributaries along the flanks of valley walls led to the formation and outward flow of glacial ice; debris falling from the talus slopes above became concentrated and deformed to create the lineated glacial debris cover. As LDA grew and coalesced, they merged between massifs and in valley centers, and began to flow down-gradient, forming LVF, ultimately creating large valley glaciers with divides, local piedmont-type glaciers, and very large valley glacial landsystems (Head et al., 2006a,b). The location and distribution of these features (Fig. 1) strongly suggest regional intermontaine valley glacial systems whose locations are dictated by topographic configurations (dichotomy boundary scarps, massifs, valleys and craters) conducive to accumulation and preservation of snow and ice and the formation of rock debris cover (Benn et al., 2003). Several topographic and morphologic relationships suggest that some valley glacial systems may be partly fed from local plateau icefields (Figs. 2C, 8).

In summary, the Deuteronis–Protonilus region (Fig. 1) was an area of active and very widespread glaciation during parts of the Amazonian. The strong geomorphic similarities between lobate deposits along the dichotomy boundary between 30° and 50° N with terrestrial cold-based glaciers and glacial deposits has led to hypotheses for geologically recent (Late Amazonian–age) mid-latitude glaciation (e.g., Head et al., 2006a,b). The key to these studies has been to identify individual landscape elements on Mars and to match them with terrestrial counterparts (e.g., Marchant and Head, 2007). Building on this work, the next logical step is to integrate a landsystems approach (e.g., Evans, 2003), whereby assemblages of landforms over wide spatial scales may be used to deconvolve the evolution and maturation of glacial cycles on Mars. The characteristics of these features compare quite favorably to terrestrial counterparts that formed during the build up, maturation (glacial overriding of mountain topography), and ultimate sublimation of Miocene-age cold-based glaciers in the Antarctic Dry Valleys (ADV) (Denton et al., 1993; Marchant et al., 1993). During the waning stages of this glacial overriding event, alpine glaciers formed in the lee of emerging nunataks and at the head of alcoves in otherwise ice-free valleys. Rockfall along the sides of these alcoves, in concert with sublimation of dirty ice, produced classic debris-covered glaciers (e.g., Marchant and Head,
2006, 2008). Some of the extant debris-covered glaciers in the ADV may have formed during this time, as long ago as 8.1 Ma (M창hant et al., 2002). These provide important insight into the interpretation of glacial deposits in the northern mid-latitudes of Mars and may lead to a better understanding of the behavior of ice sheets with time and how they behave in the distinctive mid-latitude topography of the dichotomy boundary.

Under what conditions might these features have formed on Mars? Recent GCM analyses show that the major accumulations of water ice in the equatorial regions (to form the Late Amazonian tropical mountain glacier deposits) most likely involved precipitation and deposition during periods of high obliquity. We examined the fate of tropical mountain glaciers formed at ~45° obliquity (Forget et al., 2006, 2007) following a return to lower obliquity (~35°) (Madeleine et al., 2007, 2009) and found that a meteorological consequence of this large equatorial reservoir was the formation of a thick cloud belt in the northern mid-latitudes of Mars. The thermodynamic state of the atmosphere results in increased meridional circulation, a strong eastward jet during northern winter, and associated stationary planetary waves. If the atmosphere is relatively dusty, a condition expected in this configuration, then this new water cycle favors condensation and precipitation and preservation of water ice in the areas described above to depths approaching 1000 m during a ~50 ky high obliquity cycle (Fig. 8). Guidelines from the GCMS can be used to model the snow and ice accumulation and flow behavior in this latitude region and assess the characteristics and evolution of accumulating ice in terms of flow patterns (Fastook et al., 2008a,b) in a manner similar to analysis of tropical mountain glaciers (Fastook et al., 2008b). Accumulation in alcoves develops local downslope flow, in time leading to convergence and coherent down-valley flow, and the formation of a well-developed valley glacier system extending to the mouths of the major valleys. The glaciers eventually extend out of the valleys and into the adjacent northern lowlands, in a configuration comparable to observations of the deposits (e.g., Fastook et al., 2008a,b). Expansion of the model clearly shows reproduction of local flow patterns (Fastook et al., 2008a,b) observed in images (Figs. 3–7). These analyses provide strong support for the interpretations and help to assess the time scales and velocities involved in the valley glaciation processes. The broad distribution of snow and ice accumulation mapped out by the GCM simulations (Madeleine et al. 2009) (Fig. 8A) raise the question of whether the LDA and LVF developed solely as alpine-type valley glacial landsystems (e.g., Rea and Evans, 2003). Preliminary analysis of the glacial components of higher altitude local or regional plateau glacial deposits and sites of former valley glaciation and debris-covered glaciers (Madeleine et al., 2007, 2009); and 7) Glacial flow models predict the general configuration and morphology of the observed deposits interpreted to be integrated glacial valley landforms (Fastook et al., 2008b). Recent SHARAD data have shown evidence for significant quantities of buried ice in mid-latitude LDA and LVF deposits (Holt et al., 2008; Plaut et al., 2009), adding confidence to this interpretation.

Acknowledgements

We gratefully acknowledge support from the Mars Exploration Program Mars Express HRSC grant JPL 1237163, and the Mars Data Analysis Program grants NNG05GQ44G and NNX07AN95G to JWH and to the Mars Fundamental Research Program Grant NNX06AE32G to DRM. Thanks to the HiRISE and CTX teams for use of high-resolution image data, and to the Mars Express HRSC team for production of high-quality digital elevation models.

References
