Flow patterns of lobate debris aprons and lineated valley fill north of Ismeniae Fossae, Mars: Evidence for extensive mid-latitude glaciation in the Late Amazonian

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A variety of Late Amazonian landforms on Mars have been attributed to the dynamics of ice-related processes. Evidence for large-scale, mid-latitude glacial episodes existing within the last 100 million to 1 billion years on Mars has been presented from analyses of lobate debris aprons (LDA) and lineated valley fill (LVF) in the northern and southern mid-latitudes. We test the glacial hypothesis for LDA and LVF along the dichotomy boundary in the northern mid-latitudes by examining the morphological characteristics of LDA and LVF surrounding two large plateaus, proximal massifs, and the dichotomy boundary escarpment north of Ismeniae Fossae (centered at 45.3°N and 39.2°E). Lineations and flow directions within LDA and LVF were mapped using images from the Context (CTX) camera, the Thermal Emission Imaging Spectrometer (THEMIS), and the High Resolution Stereo Camera (HRSC). Flow directions were then compared to topographic contours derived from the Mars Orbiter Laser Altimeter (MOLA) to determine the down-gradient components of LDA and LVF flow. Observations indicate that flow patterns emerge from numerous alcoves within the plateau walls, are integrated over distances of up to tens of kilometers, and have down-gradient flow directions. Smaller lobes confined within alcoves and superposed on the main LDA and LVF represent a later, less extensive glacial phase. Crater size-frequency distributions of LDA and LVF suggest a minimum (youngest) age of 100 Ma. The presence of ring-mold crater morphologies is suggestive that LDA and LVF are formed of near-surface ice-rich bodies. From these observations, we interpret LDA and LVF within our study region to result from formerly active debris-covered glacial flow, consistent with similar observations in the northern mid-latitudes of Mars. Glacial flow was likely initiated from the accumulation and compaction of snow and ice on plateaus and in alcoves within the plateau walls as volatiles were mobilized to the mid-latitudes during higher obliquity excursions. Together with similar analyses elsewhere along the dichotomy boundary, these observations suggest that multiple glacial episodes occurred in the Late Amazonian and that LDA and LVF represent significant reservoirs of non-polar ice sequestered below a surface lag for hundreds of millions of years.

1. Introduction

The Late Amazonian geological history of Mars has been dominated by landforms resulting from a variety of ice-rich processes (e.g., Squyres, 1979; Lucchitta, 1981; Carr, 1996; Neukum et al., 2004; Head et al., 2005; Head and Marchant, 2009; Carr and Head, 2009). A class of landforms that have been attributed to the flow of ice-rich material includes lobate debris aprons (LDA) and lineated valley fill (LVF). These features are found in the southern and northern mid-latitudes (between 30° and 50° latitude) of Mars (Squyres and Carr, 1986) and are particularly well represented in the so-called fretted terrain (Sharp, 1973) along the dichotomy boundary from ~30°N to 50° latitude and ~10°E to 80°E longitude. Within the fretted terrain, LDA originate from and surround isolated massifs and escarpment walls, and LVF form parallel ridges between topographic confinement such as fretted valleys (Squyres, 1979). Recent analyses of post-Viking datasets have shown large-scale LDA and LVF to be part of integrated, continuous flow systems (Head et al., 2006a,b, 2009b; Morgan et al., 2009). As the integrated relationships between LDA and LVF are still being corroborated globally, the features are herein described separately.

While there is agreement that ice was involved in LDA and LVF formation, its origin and the amount of ice needed to form LDA and LVF is debated. Three main sources of ice have been proposed: (1) seasonal deposition of frost through direct condensation of ice from the atmosphere (Squyres, 1978), (2) ground ice, relict from ancient aquifers (Lucchitta, 1984; Carr, 2001), and (3) atmospheric precipitation as snowfall (Head et al., 2006a). A number of formation styles for LDA and LVF have also been proposed, each
considering a spectrum of ice contents: (1) frost creep or gelification (Carr and Schaber, 1977), (2) rock glacier flow (ice-cemented debris) (Squyres, 1978; Mangold, 2003; Pierce and Crown, 2003), and (3) debris-covered glacier flow (nearly pure ice overlain by a debris layer) (Li et al., 2005; Head et al., 2006a,b). The convex-up, steep terminus profile of LDA is the typical product of flow of ice-rich bodies and has thus tended to disfavor hypotheses calling on slow-moving, upper-surface processes involving little interstitial ice such as frost creep or gelification (Squyres, 1978; Li et al., 2005). Rather, LDA and LVF appear to have moved en masse, flowing away from the base of escarpments, and thus being most similar to rock-glaciers or debris-covered glaciers on Earth (Squyres, 1978; Kochel and Peake, 1984; Pierce and Crown, 2003; Li et al., 2005). Associations with large-scale glacial-like landforms (e.g., eskers, moraines, and erosional scours) have also pointed toward a glacier origin for LDA and LVF (Kargel and Strom, 1992). Disagreements over rock glacier nomenclature and classifications in the terrestrial literature (e.g., Hamilton and Whalley, 1995) make it difficult to apply a rock glacier classification scheme to Mars (Whalley and Azizi, 2003). Here, we define the term “rock glacier” as being a debris-rich feature formed by the deformation and mobilization of interstitial ice and ice/ice. Although the term “debris-covered glacier” has been used as a rock glacier sub-type having remnant cores of glacier ice (e.g., Clark et al., 1994), we use “debris-covered glacier” here to describe a nearly pure ice body overlain by a thin till layer that is generated from the build-up of rock-fall and aeolian material as near-surface ice is sublimated. A classic example of a slow-moving debris-covered glacier on Earth is the Mullins glacier, a very slow-moving cold-based glacier in the Antarctic McMurdo Dry Valleys (Marchant and Head, 2006, 2007), Head et al. (2009b) outlined a series of criteria to assist in the identification of debris-covered glacial-related terrains on Mars. These features, and their interpreted terrestrial analog (in parentheses), provide a basis on which to assess whether glaciation was likely to have shaped the geomorphology of terrains on Mars. These include: (1) alcoves, which are defined as theater-shaped indentations in valley and massif walls (local snow and ice accumulation zones and sources of rock debris with cold- and wet-based glacial landforms on Earth (e.g., Head et al., 2006a). These similarities in morphologies have been documented in a number of locations along the martian dichotomy boundary, each emphasizing the role of debris in preserving underlying ice-rich bodies (Fig. 1) (Head et al., 2006a,b, 2009b; Levy et al., 2007; Dickson et al., 2008; Morgan et al., 2009; Kress et al., 2009). Further support for a debris-covered glacier origin has come from recent radar data from the SHALLOW RADar (SHARAD) instrument, which indicate that LDA in both hemispheres consist of nearly pure ice with a surface till layer no thicker than about 15 m (Holt et al., 2008; Plaut et al., 2009; Safaeinili et al., 2009). A debris-covered glacier interpretation for LDA and LVF has thus been favored, where LDA and LVF represent debris-covered and stagnant remnants of glacier ice. The purpose of this paper is to further test the hypothesis that LDA and LVF resulted from debris-covered glacier flow by examining LDA and LVF in a region along the dichotomy boundary north of Ismeniae Fossae (Figs. 1 and 2) using a set of morphological criteria established for recognizing debris-covered glacier features on Mars (Head et al., 2009b). The Ismeniae Fossae study region is uniquely positioned in one of the northernmost portions of the dichotomy boundary and offers the opportunity to explore the relationships and interactions between LDA and LVF emanating from isolated plateaus and proximal massifs occurring away from the typical patterns of LVF in the fretted valleys (Head et al., 2006b; Levy et al., 2007). We build on and expand prior documentation of this region (Nahm et al., 2006; Baker et al., 2009) to provide a more detailed analysis of these unique LDA and LVF characteristics. Furthermore, on the basis of a range of terrestrial analogs most likely to apply to the recent cold-desert environment of Mars (e.g., Marchant and Head, 2006, 2007), Head et al. (2009b) outlined a series of criteria to assist in the identification of debris-covered glacial-related terrains on Mars. These features, and their interpreted terrestrial analog (in parentheses), provide a basis on which to assess whether glaciation was likely to have shaped the geomorphology of terrains on Mars. These include: (1) alcoves, which are defined as theater-shaped indentations in valley and massif walls (local snow and ice accumulation zones and sources of rock debris

![Fig. 1. Context map of the fretted terrain along the dichotomy boundary from 0°E to 85°E and 25°N to 55°N. The region studied in this paper is outlined (solid inset box), as well as the study regions of previous studies of LDA and LVF that have found evidence for Late Amazonian mid-latitude glaciation (dashed inset boxes). Mercator projection with MOLA gridded topography overlaying MOLA shaded relief.](image-url)
cover), (2) parallel arcuate ridges facing outward from these alcoves and extending down-slope as lobe-like features (deformed flow ridges of debris), (3) shallow depressions between these ridges and the alcove walls (zones originally rich in snow and ice, which subsequently sublimated, leaving a depression), (4) progressive tightening and folding of parallel arcuate ridges alongside adjacent lobes or topographic obstacles (constrained debris-covered glacial flow), (5) progressive opening and broadening of arcuate ridges where there are no topographic obstacles (unobstructed flow of debris-covered ice), (6) circular to elongate pits in lobes (differential sublimation of surface and near-surface ice), (7) larger tributary valleys containing LVF formed from convergence of flow from individual alcoves (merging of individual lobes into LVF), (8) individual LVF tributary valleys converging into larger LVF trunk valleys (local valley debris-covered glaciers merging into larger intermontane glacial systems), (9) sequential deformation of broad lobes into tighter folds, chevron folds, and finally into lineated valley fill (progressive glacial flow and deformation), (10) complex folds in LVF where tributaries join trunk systems (differential flow velocities causing folding), (11) horseshoe-like flow lineations draped around massifs (differential glacial flow around obstacles), (12) broadly undulating along-valley floor 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), (13) integrated LVF flow systems extending for tens to hundreds of kilometers (inter-montane glacial systems), (14) rounded valley wall corners where flow converges downstream, and narrow plateau remnants between LVF valleys (both interpreted to be due to valley glacial widening). Taken together, the occurrence of these types of features was interpreted to represent the former presence of active debris-covered glaciers and valley glacial systems on Mars (e.g., Head et al., 2006a,b). In these areas, 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 integrated glacial systems. We employ these criteria to assess evidence for similar features and processes in the study area. Candidate flow directions for LDA and LVF are interpreted from a morphological map, which are then compared with MOLA topography to determine down-gradient flow components. Finally, ages of LDA and LVF are determined from crater size-frequency distributions and superposition relationships.

2. Geological setting

2.1. Plateaus and escarpments

The study region encompasses one of the northernmost areas of the fretted terrain along the dichotomy boundary in the Deuterolius–Protonilus region, north of Ismeniae Fossae (43.2–47.3°N and...
36.3°–42.0°E longitude, Figs. 1 and 2). Features within the study area have been extensively used in Viking-era images as examples of typical lobate debris aprons (Carr and Schaber, 1977, Fig. 2; Squyres, 1978, Figs. 7 and 8; Squyres, 1979, Figs. 1 and 2; Lucchitta, 1984, Fig. 7; Squyres, 1989, Figs. 15 and 17). Morphological mapping of portions of the study region using Viking images has also been completed (Kochel and Baker, 1981; Kochel and Peake, 1984). In these studies, broad morphological features were recognized, including observations of the large spatial extents of LDA and the interactions between adjacent LDA surrounding steep-walled plateaus and smaller mesas. Steep escarpments (>10° slope) within the study area occur as a continuous dichotomy boundary escarpment, the walls of two large, elongate (60 km and 120 km long) plateaus, and several 10–20 km wide proximal massifs (Figs. 2–4). These features appear to be the erosional remnants of the northernmost rim of a Noachian-aged (Tanaka et al., 2005), highly modified impact basin approximately 350 km in diameter, the interior of which is Ismeniae Fossae (Schultz et al., 1982) (Fig. 2). The two large plateaus (Plateaus 1 and 2) are arcuate in planform and have reliefs of 2.5 km to nearly 4 km above the surrounding plains, reaching peak elevation at about 500–800 m above datum (Fig. 3). These large elevations are likely remnant crater rim elevations as they are similar in magnitude to a rim-like escarpment along the southern edge of the Ismeniae Fossae (Fig. 2). The dichotomy boundary escarpment has smaller relief at ~2–2.5 km above the surrounding plains (Figs. 2 and 3) and represents erosion of the interior portions of the Ismeniae Fossae basin (Fig. 2). The planform perimeters of the two plateaus, the dichotomy boundary escarpment, and proximal massifs are highly irregular, consisting of numerous small to large (<5 km to 15–20 km wide) “bite-like” (Nahm et al., 2006) alcoves (Figs. 3 and 5). Many of the larger alcoves exhibit circular planform shapes, and some may represent highly modified remnants of ancient impact craters.

2.2. LDA and LVF

In general, well-developed LDA and LVF surround only steep escarpments (>10° slope) (Fig. 4), originate from alcoves within the escarpment walls, and extend for tens of kilometers at slopes of <3° before terminating abruptly at steeper slopes of 4–7°. The lobate outlines of the main apron bodies surrounding Plateaus 1 and 2 and the dichotomy boundary escarpment are well-defined by this steep lobate front on a regional slope map (Fig. 4). A typical topographic profile of LDA and LVF exhibits a convex-up shape with maximum relief of ~0.5–1.2 km from the base of the abutting escarpment to the surrounding plains (Fig. 3). LDA and LVF within the study region are most extensive and continuous and best developed surrounding Plateaus 1 and 2 and along the dichotomy escarpment (Fig. 5). These aprons are herein referred to as the major LDA and LVF. LDA and LVF are also found surrounding isolated massifs, mesa clusters, and the interiors of craters; these are not integrated with LDA and LVF surrounding the steep escarpment walls of the plateaus and dichotomy boundary and are herein named minor LDA and LVF. While the morphologies of minor LDA and LVF are not entirely distinct from the morphologies of major LDA and LVF, there are some textural differences that may indicate differences in material properties, such as ice content.

![Fig. 4. Slope map of study region derived from MOLA gridded topography. Lobate debris aprons are found to originate only along steep (>10°) escarpments (red) and generally have slopes of <3° with steeper termini of 4–7°. Sinusoidal projection, with a central meridian set at 39.2°E. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.]

3. Morphological mapping

Images from the Mars Reconnaissance Orbiter (MRO) Context (CTX) camera (at ~6 m/pixel resolution), were used to create a morphological map of the study area (Fig. 5); THEMIS VIS and HRSC images were used in the few locations where no CTX images were present. All images were processed and projected using ISIS software and then co-registered in ArcMap for morphological mapping. Large features were outlined, including LDA and LVF, tops of plateaus, steep escarpment walls and proximal massifs, and the surrounding plains. In some places where they were prominent, subdivisions within the major morphological features were mapped. Lineations within the LDA and LVF unit were mapped based upon ridge and furrow textures observed at the 1:50,000 scale. Mapped lineations follow prominent ridges and the rims of depressions with no regard to orientation. Ridges associated with modification processes such as aeolian activity (i.e. dunes) were morphologically distinguished and were not included in the mapping process.

4. Results

4.1. Flow patterns

Lineations within major LDA and LVF show highly integrated flow patterns that extend from numerous alcoves within the escarpment, plateau, and massif walls, merge together between these escarpments, and flow down-gradient into the surrounding plains (Fig. 5). LDA and LVF are thus observed to be a single entity formed from the coalescing of multiple individual lobes with flow patterns mainly controlled by the adjacent and underlying topography, similar to terrestrial glacial landsystems (e.g., Evans, 2003).

Several examples from major LDA and LVF typify the flow patterns observed. Fig. 6 depicts a segment of LDA along the southern wall of Plateau 1, formed of a system of individual, coalesced lobes. Flowlines emerge as parallel ridges nearly perpendicular to the wall of Plateau 1 from several small alcoves (Figs. 6B and 7A), and bend into concentric lobate patterns down-slope (Figs. 6B and 7B). Individual lobes merge with adjacent lobes to form a continuous apron extending ~25 km from the base of Plateau 1. LDA flow is also funneled to form piedmont-like lobe fronts where there are topographic depressions at the terminus, such as craters (Figs. 6B and 7C). Flowlines, likely sourced in small alcoves in the middle of Fig. 6A, also wrap around a ~5 km wide obstacle, illustrating the control topography has in directing LDA flow. Arcuate, concentric, moraine-like ridges delineate a small lobe nearly confined to an alcove in the top middle of Fig. 6A (see Fig. 8 for a close-up view). The ridge patterns from this smaller lobe broaden where unconfined by the alcove walls and appear superposed on the main debris apron of Plateau 1 (Fig. 8, and discussion below).

Another example includes a 50-km-long, westward flowing LDA and LVF system on the western flank of Plateau 1 (Fig. 9). Parallel sets of flowlines emerge from two large, theater-headed alcoves and several smaller alcoves, which rapidly bend westward, merge,
and straighten to form LVF between the northern wall of Plateau 1 and the southern wall of an elongate massif (Fig. 9B). As the LVF becomes unconfined from the plateau and massif walls, the flowlines bend outward, and the resulting LDA forms a broad lobe that terminates into the adjacent plains as a steep, arcuate scarp (Fig. 4). Where a ~1 km wide obstacle is encountered, flowlines wrap around the obstacle and become more prominent and compressed (Figs. 9B and 7E); this deflection forms a smaller subsidiary lobe to the south. The perimeter of the lobe terminus of the LDA system is delineated by a linear depression (Fig. 7F), which may be analogous to a sublimed ice-cored moraine. Numerous depressions are also observed on the main apron body (Fig. 7E and F), which may represent additional areas where sublimation of near-surface ice was focused. Individual flow lobes emerging from the walls of proximal massifs are also observed to merge with the main large lobe. These massif lobes have lineations that start perpendicular to the massif wall and then bend to form concentric lobe patterns down-slope (Fig. 9B). Flow lineations emerging from massifs within major LDA and LVF of Plateau 1 may also occur as wall-parallel sets of lineations (Fig. 9B), similar to flow patterns of LDA surrounding isolated massifs (Fig. 12D).

Similar patterns are also observed along the dichotomy boundary escarpment (Fig. 10). Although small, narrow, well-defined alcoves are not as pronounced as in the walls of Plateau 1, broad alcoves do occur, separated by thin ridges of plateau material (Fig. 5). Some of these broad alcoves may have originated as impact craters, as shown by their broadly circular planforms; similar alcove morphologies are observed in Plateaus 1 and 2. In one location along the dichotomy boundary, LDA is found in a ~10 km crater perched 2–2.5 km above the surrounding plains (Figs. 3 and 10). Although lineations are not very pronounced in the LDA within the crater, the lineations that do occur suggest that flow is directed from the crater wall to an outlet along its northern rim (Fig. 10B). The topographic profile of the crater LDA is markedly convex-up; the profile then becomes steeper (>10°) where it transects the dichotomy boundary escarpment transitioning to a more gradually sloped (1–2°) apron surface at the base of the escarpment (Fig. 3). Flow patterns emerging from the base of the dichotomy boundary escarpment exhibit similar characteristics to LDA flow patterns surrounding Plateau 1. Individual lobes are expressed by lineations perpendicular to the escarpment wall, which transition into concentric lobe patterns down-slope (Figs. 10B and 7G). Where the flow encounters two massifs, lineations are compressed and bend around the massif walls (Figs. 10B and 7G and H). The eastern branch of this diverted flow continues down-slope to merge with another lobe originating along the dichotomy boundary escarpment (Figs. 10B and 7H). An additional lobe sourced from a massif wall converges with the integrated flow pattern (Figs. 10B and 7I) before the whole system terminates as a steep escarpment into the adjacent plains. Together, this flow system integrates lobes from the dichotomy boundary escarpment and proximal massifs over a distance of over 25 km.

4.2. Topographic control on flow

The interpreted flow directions in each of the LDA and LVF examples (arrows, Figs. 6B and C, 9B and C, and 10B and C) are nearly always perpendicular to MOLA-derived topographic contours (Figs. 6C, 9C, and 10C) suggesting primarily down-gradient, gravitationally-driven flow. Encounters with topographic obstacles also compress and divert flow (Figs. 6B, 9B, and 10B) and topographic divides partition flow into multiple directions (e.g., Fig. 10B). We assume that the present surface topography of LDA and LVF grossly mimics the underlying basement topography; this is similar to the surface topography of terrestrial valley glacier systems (Eyles, 1983; Benn et al., 2003). Large ice sheets and plateau
icefields, however, are thick enough to establish their own flow regimes that often override and do not “feel” the underlying topography (Evans, 2003; Rae and Evans, 2003; Marchant and Head, 2006, 2008; Fastook et al., 2008a, 2009; Head et al., 2009b). Although evidence for “upslope flow” is not observed in the study region, flow lineations that appear at odds with underlying topography in the Coloe Fossae region have been used to suggest flow reversal and a former glacial highstand as much as 920 m above the current LVF surface (Dickson et al., 2008; see also Dickson et al., 2009). If a regional ice sheet did occur in our study region, as suggested by several analyses (see summary in Head et al. (2009b)), evidence for its existence is not expressed in the mapped flow patterns of LDA and LVF. This emphasizes the point that preserved flow patterns may only represent the last phases of glaciation and that more extensive ice, if it existed, may not have been sufficiently covered by debris to leave geomorphic traces at all locations.

4.3. Variations within mapped LDA and LVF

Major LDA and LVF are formed by well-integrated flow systems that extend for tens of kilometers from alcoves to lobate termini.
into the surrounding plains. However, not all of the mapped LDA and LVF are part of the major LDA and LVF. These minor LDA and LVF account for ~32% of the total mapped LDA and LVF within the study region and may be divided into three groups based upon their spatial locations, association with massifs, and textural patterns. The first minor LDA and LVF group is isolated massif LDA. These LDA account for 6% (area = 734 km²) of the total LDA and LVF material and only surround small massifs that are isolated from other massifs within the flat-lying plains (Figs. 11 and 12C and D). Although a coalescence of individual lobe-like flow patterns is observed in one large isolated massif LDA (Fig. 12C), the majority of isolated massif LDA have only concentric, wall-parallel sets of flowline ridges (Fig. 12D). Few well-developed alcoves are observed in massifs associated with these apron types, and their termini generally extend <10 km from the base of the massif. Another minor LDA and LVF group, mesa-cluster LDA and LVF (Fig. 11), account for 10% (1304 km²) of the total LDA and LVF area and occur surrounding degraded clusters of mesas or small massifs north of ~46°N. These LDA and LVF exhibit less well-defined flowline patterns than the major LDA and LVF (Fig. 12E and F), and do not extend far into the surrounding plains. The termini of mesa-cluster aprons are also poorly defined, with more gradational morphological transitions with the adjacent plains (Fig. 12F). We also classified LDA found within the interiors of large craters as a separate group (Fig. 11). These crater interior LDA are contained within three large craters south of 45°N and account for 12% (1526 km²) of the mapped LDA and LVF material. These features, while occupying the interior of craters, differ from the classic concentric crater fill deposits that have been mapped in both hemispheres in these latitude bands (e.g., Squyres, 1979; Squyres and Carr, 1986; Levy et al., 2009). Concentric crater fill, while interpreted to be of the same material as LDA and LVF (Squyres, 1979), typically consists of concentric lineations within craters >1 km in diameter, with the fill typically occupying the entire crater floor. Several examples.
of concentric crater fill occur in the study region (Fig. 5). Crater interior LDA within the study region, however, do not occupy the entire crater interior and are most similar to dichotomy boundary LDA with wall-perpendicular lineations and convex-up profiles that end as steep termini up to 15 km from the crater wall (Figs. 5 and 12A and B). Lineations, however, are not always present within crater interior LDA, and flow patterns are not as pronounced as the

Fig. 9. A >50 km system of LDA and LVF originating from the northern wall of Plateau 1 and proximal massifs (see context map, Fig. 5); inset boxes in panel A show the locations of Fig. 7D–F. (A) Mosaic of CTX images P17_007834_2259, P14_006687_2271, and P17_007544_2247. (B) Morphological map of CTX images. The map units are the same as those in Fig. 5. Arrows give the interpreted flow directions based upon the mapped flowlines (green). Flowlines emerge from large alcoves in the plateau walls and massifs and bend westward to form lineated valley fill, which merges with other flowlines and debouches into the plains as a large lobe (see text for description). (C) MOLA-derived contours at 50-m intervals with interpreted flow directions (arrows) superposed; flow patterns are generally perpendicular to the contour lines, supporting down-gradient flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 10. Portion of a lobate debris apron originating from the dichotomy boundary escarpment (see context map, Fig. 5); inset boxes in panel A show the locations of Fig. 7G–I. (A) Mosaic of CTX images P17_007834_2259 and P14_006476_2258. (B) Morphological map of CTX images. The map units are the same as those in Fig. 5. Arrows give the interpreted flow directions based upon the mapped flowlines (green). Flowlines appear to emerge from a large crater and small alcoves in the plateau walls, bend downslope to form lobes that compress and are diverted by massifs, and coalesce with other lobes to form the broad lobate debris apron observed. (C) MOLA-derived contours at 50-m intervals with interpreted flow directions (arrows) superposed; flow patterns are generally perpendicular to the contour lines, supporting down-gradient flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
major LDA and LVF (Fig. 12A). One occurrence of LDA in the southeast corner of the study region was left ungrouped (Fig. 11). Although this specific LDA resembles major LDA and LVF extending from the dichotomy boundary escarpment, it does not emerge from a steep escarpment found elsewhere within the study region, nor does it fall into any of the other LDA classifications.

4.4. Summary

Based on the criteria for identification of debris-covered glacier-related terrains on Mars outlined by Head et al. (2009b), evidence of past debris-covered glaciers has been found in the north Ismeniae Fossae area (Fig. 5). This evidence includes: (1) alcoves, which are defined as theater-shaped indentations in valley and massif walls (Figs. 7A and D, 8, 15, and 16), (2) parallel arcuate ridges facing outward from these alcoves and extending down-slope as lobe-like features (Figs. 7B, G and H and 8), (3) progressive tightening and folding of parallel arcuate ridges where abutting adjacent lobes or topographic obstacles (Fig. 7E, G, and H), (4) progressive opening and broadening of arcuate ridges where there are no topographic obstacles (Figs. 8 and 9), (5) circular to elongate pits in lobes (Fig. 7B, C, E, F, and I), (6) individual LVF tributary valleys converging into larger trunk valleys (Fig. 9), (7) sequential deformation of broad lobes into tighter folds, chevron folds, and finally into local examples of linedate valley fill (Figs. 9 and 10), (8) complex folds where tributaries join trunk systems (Fig. 10), (9) horse-shoe-like flow lineations draped around massifs (Figs. 6, 7E and H, 9, 10), (10) integrated flow systems extending for tens of kilometers (Figs. 6, 9 and 10), and (11) rounded valley wall corners where flow converges downstream, and narrow plateau remnants between valleys (Figs. 5, 9 and 10). Therefore, taken together, the morphological patterns of LDA and LVF and adjacent bedrock north of Ismeniae Fossae are consistent with the interpretation that they were formed by flow of debris-covered glaciers. We interpret these features to have resulted from snow and ice accumulating in alcoves at high elevation. Together with rock debris shed from adjacent steep walls, compaction and thickening of ice created debris-covered glaciers that flowed down-slope, merging with other ice lobes to form integrated glacial systems. We now address the question of the timing of these deposits and detailed assessment of their formation and evolution.

5. Craters and timing of formation

5.1. Crater morphologies

Counts of craters, including a variety of crater morphologies, were conducted on all of the mapped LDA and LVF surfaces using 16 CTX images. Of the 1332 craters counted, the maximum diameter observed for all crater types was 826 m with a minimum crater diameter of 22 m and an average crater diameter of 116 m. Three main groups of crater morphologies were recognized on
LDA and LVF surfaces within our study region: (1) bowl-shaped craters, (2) ring-mold craters (Kress and Head, 2008), and (3) flat-topped knobs.

Bowl-shaped craters exhibit the characteristics of typical simple impact craters. We distinguish between fresh morphologies (Fig. 13A), exhibiting sharp rims and smooth, bowl-shaped interiors, and degraded morphologies (Fig. 13B), which exhibit more irregular rims but maintain smooth floors. Fresh and degraded bowl-shaped craters account for about 75% of the total crater population, with fresh morphologies contributing about 41% and

![Fig. 12. CTX views of LDA and LVF types showing the morphology of mapped LDA and LVF units, with contacts shown (white lines)](for context, see Fig. 11). (A) and (B) Crater interior LDA exhibit wall-perpendicular lineations that are generally poorly defined or absent from the LDA surface. These LDA are distinct from concentric crater fill as they do not have concentric lineations and do not completely fill the crater interior (CTX images P17_007834_2259, P17_007768_2240, and P18_007913_2244). (C) and (D) Isolated massif LDA are not integrated with any large-scale pattern and occasionally exhibit individual lobate patterns with prominent ridges (C), but more often exhibit concentric wall-parallel lineations (D) (CTX images P17_007557_2256 and P18_007979_2264). (E) and (F) Mesa-cluster LDA and LVF exhibit highly degraded surface textures with dune-like features and pits (E) and poorly defined boundaries that appear to grade into the surrounding plains (F). Lineations, while occasionally present, are usually absent or highly obscured (CTX images P17_007757_2256 and P17_007623_2271). See text for description of LDA and LVF groups.
Fig. 13. CTX views of crater morphologies observed within the study region, including bowl-shaped craters (A and B), ring-mold craters (C–F), and flat-topped knobs (G). Fresh (A) and degraded (B) bowl-shaped craters are ubiquitous across the study region. Ring-mold craters (Kress and Head, 2008) can be classified as pit-type (C), central mound (D), central plateau (E), and multi-ring (F). Some flat-topped knobs (G) are interpreted to be erosional remnants of ring-mold craters, supported by the observation of transitional morphologies (H).
degraded about 59% of all bowl-shaped craters (Table 1). The average diameter of bowl-shaped craters is 101 m, with a maximum crater diameter of 826 m and a minimum of 22 m. As expected from the widening effects of crater degradation (loss of rim crest and shallowing of the floor due to infilling: Head, 1975), degraded bowl-shaped craters have an average diameter of 113 m, larger than the average diameter of fresh bowl-shaped craters at 85 m. 

Ring-mold craters (Kress and Head, 2008) exhibit unusual morphologies, with complex interior features typically surrounded by a rimless, circular moat. These crater types were originally interpreted to result from a degradational sequence involving the sublimation and deflation of an icy-substrate supporting the original simple crater shape (Mangold, 2003; McConnell et al., 2007). Recent analysis by Kress and Head (2008), however, suggests that ring-mold craters are the result of impacts into a nearly pure ice substrate thought to reside below a thin (tens of meters) debris layer within LDA features. While bowl-shaped craters were observed adjacent to ring-mold craters, the relatively small crater diameters of bowl-shaped craters suggested that these impacts did not penetrate the protective debris layer to the ice below. Following the ring-mold crater classification of Kress and Head (2008), four ring-mold crater morphologies are recognized on apron surfaces in the study region: central pit (Fig. 13C), central mound (Fig. 13D), central plateau (Fig. 13E), and multi-ring (Fig. 13F). Diameter measurements for these types of craters are only approximate, as the effects of impacting into an icy substrate and post-impact degradational processes have obscured the recognition of “true” crater diameters. In most cases, crater diameters were measured to the edge of the outer-most recognizable circular moat surrounding the interior features. Ring-mold crater morphologies account for about 9% of all craters documented (Table 1). The average diameter of ring-mold craters is 221 m, with a maximum diameter of 697 m and a minimum diameter at 68 m. 

A third class of craters within the study region is “flat-topped knobs”. These craters are not true crater forms, as they are small circular plateaus that are isolated and raised above the surrounding terrain (Fig. 13G). Transitional morphologies between central plateau ring-mold craters and flat-topped knobs are observed (Fig. 13H), suggesting that some flat-topped knobs may have originated as ring-mold craters. Alternatively, flat-topped knobs could be the remnant interiors of bowl-shaped craters. Laboratory experiments suggest that the floors of craters become highly compressed during impact, producing a competent substrate “plug” confined to the interior of the crater (Schultz, 2006). Subsequent removal of less competent material surrounding this “plug” will form remnant knobs or mounds, similar to what is observed with flat-topped knobs on LDA and LVF surfaces in the study region and erosion of other friable materials on Mars (e.g., Kerber and Head, 2009). While there is little way of knowing the original diameters of flat-topped knobs, their occurrence and diameters are still valuable for analysis of the evolution and degradation of LDA and LVF surfaces (e.g., Mangold, 2003). Flat-topped knobs account for about

<p>| Table 1 | Crater count data for each of the LDA and LVF groups discussed in the text. Areas for each of the LDA and LVF groups (Fig. 11) are calculated in square kilometers and percent of total LDA and LVF area. The total number of craters, including the crater statistics (percent of total craters counted, average diameter (D), and minimum and maximum diameters) of ring-mold craters (RMC), bowl-shaped craters, and flat-topped knobs for each of the LDA and LVF groups are included, as discussed in the text. The best-fit ages for each LDA and LVF group, according to the Hartmann (2005) production function for all crater types and diameters, are given in the bottom rows. Scaled best-fit ages are also presented, calculated by scaling all ring-mold crater diameters by half, as discussed in the text. The number of craters &gt;250 m in diameter used to derive the best-fit ages are also included. |
|--------|-------------------------------------------------------------------------------------------------|---|---|---|---|---|</p>
<table>
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<th>Minor LDA and LVF</th>
<th>Isolated massif</th>
<th>Mesa-cluster</th>
<th>Crater interior</th>
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<td>RMC (% of all RMC + all bowl-shaped)</td>
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<td>4.9</td>
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<td>70</td>
<td>50</td>
<td>140</td>
<td>60</td>
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<td>Number of craters &gt;250 m</td>
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<td>5</td>
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</table>
16% of the total crater population, with an average diameter of 127 m, and a maximum and minimum diameter of 245 m and 53 m, respectively (Table 1). We also note that none of the craters within our study region are sheared, suggesting that flow within LDA and LVF is not currently active, nor have LDA and LVF been flowing since the population of craters began accumulating (Carr, 2001; Head et al., 2006a,b).

5.2. Timing of formation

Crater counts of all three crater types (total population = 1332) on all mapped LDA and LVF surfaces (“LDA and LVF material,” Fig. 5; total area = 12,929 km²) yield a best-fit age of 90 Ma for crater diameters >250 m, according to the Hartmann (2005) production function (Fig. 14). We include ring-mold craters in this crater count to represent the age during which ice was shallow enough to modify impact craters and produce ring-mold crater morphologies. If we consider only bowl-shaped craters on all LDA and LVF surfaces, we derive a younger best-fit age of 60 Ma. This younger age is better representative of the post-glacial phase within our study region, where the ice has been well below the penetration depth of craters <1 km in diameter. We also find that addition or subtraction of the flat-topped knob crater class in our counts does not affect the best-fit ages. This is due to the relatively small diameters (<245 m) of flat-topped knobs, which are not factored when determining best-fit ages using crater diameters >250 m. However, the original diameters of flat-topped knobs were likely larger, which, when considered in the crater count, may produce older ages than those calculated from observed crater and knob diameters. There is no way of knowing the original diameters of flat-topped knobs, however, leaving extrapolation of older surface ages speculative. Nevertheless, the 90 Ma age for all crater groups on all mapped aprons within our study region is slightly younger than the 100 Ma to 1.0 Ga ages derived from crater counts of crater diameters >250 m on other LDA and LVF surfaces along the dichotomy boundary (300 Ma, Mangold, 2003; 100 Ma to 1.0 Ga, Levy et al., 2007; 490 Ma and 1.1 Ga, Kress and Head, 2009; >100–500 Ma, Morgan et al., 2009).

There is also a significant down-turn in the crater distribution for crater diameters smaller than about 150 m (Fig. 14). This down-turn indicates that resurfacing of the smallest (<150 m) population of crater diameters has occurred, either from erosion or mantling by aeolian material. The removal of small crater diameters is consistent with surface deflation through sublimation of ice in the upper layers of LDA and LVF textures (Mangold, 2003; Levy et al., 2009). Resolution does not appear to be a contributor of this down-turn, as the CTX images used for crater counting have 6 m/pixel resolutions, with the ability to resolve features as small as 18 m across.

Due to the observed variation in LDA and LVF morphologies, we also examined variations in crater retention ages for each LDA and LVF group described, above (Table 1). Crater counts of all crater types on the plateau and dichotomy boundary LDA and LVF (Fig. 11 and Table 1) yield a best-fit age of 100 Ma. However, isolated massif LDA yield surface ages of 50 Ma, while mesa-cluster LDA and LVF, crater interior LDA, and an ungrouped LDA surface have surface ages of around 80 Ma (Table 1). The well developed flow patterns and continuity of the plateau and dichotomy boundary LDA and LVF suggest that these surfaces are most representative of large-scale glacial activity occurring within the study region. A derived surface age of 100 Ma for plateau and dichotomy boundary LDA and LVF (Fig. 11) is therefore assumed to best represent the minimum age for this phase of extensive glacial activity.

The younger, 50 Ma and 80 Ma, ages derived for the minor LDA and LVF groups may be indicative of several things. First, these ages may represent actual temporal differences, with renewed or late-stage glacial flow resulting in younger surface ages for minor LDA and LVF. Observational evidence for relatively young lobes confined to alcoves and superposed on the more extensive LDA and LVF (Figs. 8 and 16) is consistent with a later, less extensive Fig. 14. Log–log plot of the crater size-frequency distribution for all crater types (N = number of craters) on all LDA and LVF surfaces mapped within the study region. Comparison with Hartmann (2005) isochrons yields a best-fit age of 90 Ma for crater diameters >250 m. The heavy solid lines mark period boundaries (Noachian–Hesperian and Hesperian–Amazonian boundaries), dashed lines mark period subdivisions (early, middle, and late), and the light solid line is the derived best-fit isochron. A down-turn in the number of craters per diameter bin per unit area for crater diameters <150 m, suggests removal of these small crater diameters by erosion or other resurfacing events.
glacial episode. Levy et al. (2007) also suggested a relatively young age for some LDA in Nilosyrtis Mensae that exhibit concentric, wall-parallel lineations and that appear superposed on regional LVF patterns (see also Dickson et al., 2008; Morgan et al., 2009). The younger ages determined for similar morphologies of isolated massif LDA in our study region are consistent with the Nilosyrtis observations, providing further suggestions for multiple glacial episodes.

Second, the younger ages may result from differences in the ice content of the LDA and LVF material. Due to the modification effects of impacting into ice, ring-mold crater diameters may be larger than diameters produced by comparable impacts into basalt or silicate regolith (Kress and Head, 2008, 2009). If ring-mold craters are absent on LDA and LVF surfaces or have smaller diameters due to less ice-rich material or ice buried at significant depth, younger ages may result, as the largest crater diameters (>250 m) have the most control on the best-fit surface ages. Isolated massif LDA, while having a similar percentage of ring-mold craters as the plateau and dichotomy boundary LDA and LVF (13.6% versus 12.1%), have only 11% of its ring-mold craters larger than 350 m in diameter, compared to 17.4% in plateau and dichotomy boundary LDA and LVF. However, there may be smaller crater diameters, in general, on isolated massif LDA surfaces, as there are no bowl-shaped craters >350 m for isolated massifs, while ~3% of bowl-shaped craters in plateau and dichotomy boundary aprons are >350 m in diameter. Therefore, while a lower ice content may be possible for isolated massif LDA, the smaller diameters observed for all crater types on these surfaces may be a better indication of age than material properties such as ice content.

Third, there may be degradational differences between the LDA and LVF surfaces. The down-turn in the number of craters per bin per square kilometer for crater diameters <150 m indicates that all LDA and LVF surfaces are experiencing some degree of resurfacing. The degraded textural characteristics and lack of well-defined flow lineations in much of the mesa-cluster LDA and LVF (Fig. 12E and F), however, suggest that these LDA surfaces have undergone much more modification by processes such as aeolian reworking than the plateau and dichotomy boundary LDA and LVF. Parallel sets of ridges that cross-cut LDA and LVF flowlines are suggestive of aeolian resurfacing (Fig. 12E) and the highly pitted surfaces suggest that sublimation may have played a significant role in deflating the LDA material. If these degradational processes are removing the largest (>250 m) fraction of the crater population at a rate greater than these craters are produced, a younger surface age is most likely a result. The prominent ridges and patterns observed in some isolated massif LDA, however, indicate that this may not be a significant influence on some of the observed age differences.

Lastly, the variation in ages over all LDA and LVF surfaces may be an artifact of poor crater statistics, with further complications resulting from determining the “true” diameter of ring-mold craters. Subdividing LDA and LVF into groups reduces the counting area of individual minor LDA and LVF surfaces to less than 12% of the total LDA and LVF area, which also results in a reduction in the total number of craters >250 m used to determine best-fit ages. While 75 craters were used to determine the best-fit age for all mapped LDA and LVF (Fig. 5), this number breaks down to 58 craters for plateau and dichotomy boundary LDA and LVF, 7 and 6 craters for crater interior and mesa-cluster LDA and LVF, respectively, and only 2 craters for isolated massif and the ungrouped LDA (Table 1). Derived best-fit ages for minor LDA and LVF are therefore based on statistics of small populations, likely contributing to larger statistical errors; the magnitudes of these errors, however, are uncertain. Further complications in best-fit ages may result from measured ring-mold crater diameters. As discussed above, ring-mold crater diameters may be larger than diameters produced by comparable impacts into basalt or silicate regolith (Kress and Head, 2008, 2009). In an attempt to remove the effect of this diameter increase in crater size-frequency distributions of LDA and LVF surfaces, Kress and Head (2009) suggested scaling all measured ring-mold crater diameters by half; this was considered to be a conservative estimate based upon experimental studies into ice. Although the exact method for scaling ring-mold craters is still largely uncertain, decreasing our measured ring-mold crater diameters by a factor of 2 reduces the maximum ring-mold crater diameter on all LDA and LVF surfaces from 697 m to ~349 m.

Since the largest crater diameters exhibit the most control on calculated best-fit ages, a lower best-fit age results from scaling ring-mold craters. We therefore determine a scaled best-fit age for all LDA and LVF surfaces of 60 Ma, 30 Ma younger than the non-scaled age (Table 1). Scaled best-fit ages for each of the LDA and LVF groups are also 10–30 Ma younger than the non-scaled ages (with the exception of the ungrouped LDA, which has a scaled age that is 60 Ma older) (Table 1). Scaling the ring-mold crater diameters also reduces the number of craters used to determine best-fit ages by decreasing the population of craters >250 m in diameter. For example, the number of craters >250 m in diameter decreases from 75 to 47 for all LDA and LVF surfaces when ring-mold craters are scaled, and minor LDA and LVF have scaled best-fit ages that are derived from fewer than six craters (isolated massif LDA have no craters >250 m). These reductions in crater populations for diameters >250 m result in poorer statistics, particularly for minor LDA and LVF, and therefore larger uncertainties associated with the scaled best-fit ages. These uncertainties, in addition to the uncertainty of choosing an appropriate scaling factor for ring-mold crater diameters, make interpretation of the above scaled best-fit ages difficult. An improved understanding of how impact craters are modified during impacts into ice at a variety of ice depths and ice contents will help in determining an appropriate method for scaling ring-mold craters in crater size-frequency distribution calculations. Due to the large number of uncertainties involved in using scaled best-fit ages, in the following discussion we examine only non-scaled ages as they relate to mid-latitude glaciation in the study region and across the dichotomy boundary.

In summary, we find that the most recent age of extensive glacialization within the study region, as defined by craters on plateau and dichotomy boundary LDA and LVF, most likely occurred at a minimum (youngest) age of 100 Ma. Younger ages of 50 Ma and 80 Ma were determined for minor LDA and LVF that are not integrated with the plateau and dichotomy boundary LDA and LVF. While there is uncertainty in determining if these young ages represent true temporal differences in glacial flow, the observations of prominent ridges and flow patterns and the smaller bowl-shaped crater diameter populations in isolated massif LDA is most consistent with a true temporal difference. The lack of prominent flow patterns and the presence of aeolian and sublimation landforms in mesa-cluster LDA and LVF, however, suggest that more extensive degradation of these LDA and LVF surfaces is also a factor in producing younger crater retention ages. Uncertainties introduced by poor crater statistics and scaling of ring-mold craters also present problems when interpreting the significance of best-fit ages for LDA and LVF groups. Differences in ice content between LDA and LVF groups are difficult to decipher with crater statistics. The small spatial dimensions of isolated massif LDA, however, suggest that at least these LDA may not have required as much ice to form as the ice accumulation needed to produce the tens of kilometer scale patterns observed for major LDA and LVF, illustrated in Figs. 6, 9, and 10. We now present additional evidence for a young, less extensive glacial episode in the study region by examining the characteristics of small lobes nearly confined to alcoves within the walls of plateaus.
5.3. Morphological evidence for multiple glacial phases

In addition to crater retention ages, relative ages within LDA and LVF may be examined by looking at superposition relationships. Alcoves within plateau and escarpment walls are the source locations for many flow patterns within the study region. These flow patterns emerge from the alcoves as parallel sets of lineations and bend down-gradient with seamless integration with the broader LDA pattern (Fig. 15). Many of the alcoves, however, are also source locations for much smaller lobes that appear to superpose the main LDA and LVF bodies (Figs. 8 and 16) (see also Levy et al., 2007; Dickson et al., 2008; Morgan et al., 2009). These smaller lobes are generally 1–2 km in width, a few kilometers to nearly 10 km in length, and fail to extend more than 1–2 km from the outlets of their source alcoves (Figs. 8 and 16). As the lobes emerge from the confinement of the alcove walls, they broaden into piedmont-like lobes, shown by series of concentric ridges that form lobes expanding away from the alcove outlet (Figs. 8 and 16). These ridges are reminiscent of end and lateral moraines seen in terrestrial valley glaciers (Boulton and Eyles, 1979). Ridges are also observed to compress and drape around topographic obstacles, with flow re-directed through multiple outlet locations (Fig. 16A). Instead of forming integrated patterns with the main LDA and LVF aprons (e.g., Fig. 15), ridges of these small lobes appear to transect and superpose the main LDA lineations (Fig. 8).

A topographic profile of one of the lobes (Fig. 8) shows the abrupt transition from the relatively steep slope (~6–8°) of the alcove lobe to the relatively gentle slope (<5°) of the main LDA (see also Fig. 4); a more gradually sloping transitional pattern would be expected for a lobe that was well-integrated with the main LDA (e.g., Fig. 15). We also observe that while these lobes are younger than the LDA and LVF surfaces, sufficient time for aeolian modification of these superposed lobes has been allowed, illustrated by E–W oriented dunes superposed on the terminus of a lobe in Fig. 16B. These observations are consistent with previous studies describing small superposed lobes within alcoves along the dichotomy

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**Fig. 15.** Integrated lobe emerging from an alcove in the northern wall of Plateau 2 with seamless integration with the main lobate debris apron (LDA), as suggested by the continuity of the flowline pattern (B) and a gradually sloping profile (C). (A) CTX view of the inset location given in Fig. 5 (CTX image P17_007623_2271); (B) Sketch map of the CTX image. (C) Profile as delineated by the dashed line in (B). The profile starts at the top of a steep-walled alcove and transects a LVF lobe originating within the alcove. The profile of the LVF lobe has a gradational profile as it integrates with the broader LDA at the base of the plateau wall. Elevation data from HRSC DTM orbit number 1600.
boundary (Levy et al., 2007; Dickson et al., 2008; Morgan et al., 2009). This correlation is consistent with the idea of multiple glacial episodes across the dichotomy boundary. If contemporaneous, it suggests that global-scale climate change was a significant factor in the formation of LDA and LVF (e.g., Head and Marchant, 2009; Head et al., 2009b; Madeleine et al., 2009).

6. Discussion

6.1. Formational model for LDA and LVF

The flow patterns observed in LDA and LVF are very similar to the flowlines of glacial landsystems on Earth (Eyles, 1983; Benn et al., 2003; Head et al., 2009b). The scale over which LDA and LVF flow patterns are integrated precludes a formation as rock-glaciers and ice-assisted creep of talus, which are limited by an equilibrium position that does not extend for tens of kilometers from the escarpment base. Evidence of sublimation pits (Fig. 7E and F) and the presence of ring-mold craters within LDA and LVF (Fig. 13C–F) support this argument, pointing to the presence of a substantial ice-rich body at depth. The observation that many of the flow patterns of LDA and LVF are found to extend from alcoves also point to a source of ice accumulation. As seen in Antarctica, microclimates formed by depressions within high-standing topography are excellent locations for accumulating atmospheric precipitation and wind-blown snow and protecting it from subsequent loss by sublimation (Marchant and Head, 2007). The circular/arcuate morphologies of many of the alcoves (Fig. 5) suggest that some of these alcoves may have been former craters. Craters would have provided ideal catchments for precipitating or wind-blown snow, consistent with a snowfall-derived origin for debris-covered glaciers north of Ismeniae Fossae. Although the current climate of Mars does not favor the precipitation or preservation of large amounts of surface snow or ice, climatic conditions favorable to snowfall in the mid-latitudes may have occurred in the recent history of Mars. Three-dimensional atmospheric global circulation models have shown that ice may be remobilized from the poles toward the equator at high obliquity (>40°) (e.g., Mischna et al., 2003) and that deposition of significant amounts of snow and ice may take place in the mid-latitudes under plausible circumstances, including times of high dust opacities and the presence of equatorial source regions of ice (Madeleine et al., 2009). Refined global circulation modeling of the martian climate under a transition from ~45° obliquity to a moderate obliquity of 25–35° (Madeleine et al., 2007, 2009) has suggested that 500–1000 m of ice may be able to accumulate in the Deuteronilus–Protonilus Mensae region (30–50° N, 0–70° E) over an obliquity cycle of 50 ka. The current obliquity of Mars is ~25° but was likely greater in the past, with obliquity ranging from near 0° to about 65° between 50 Ma and 250 Ma.
Obliquities >25° were therefore not uncommon in Mars’ recent past, providing a consistent, recurring mechanism for delivering snow to the mid-latitude regions on Mars. The latitude dependence of LDA and LVF features (Squyres, 1979; Squyres and Carr, 1986) is consistent with obliquity-driven climate change favoring latitude-scale deposition of snow. Evidence for multiple glacial episodes within the study region and elsewhere along the dichotomy boundary (Head et al., 2009b), also suggests that climatic conditions were favorable for various degrees of debris-covered glacier formation multiple times within the last 1 Ga. These glacial events and their topographic and latitudinal distribution may be used as baselines to refine the obliquity solutions for Mars’ recent history (Fastook et al., 2008b; Head et al., 2009a) and to improve our regional- and local-scale climate models for the surface topography of Mars, including integrations with regional ice-sheet flow modeling (e.g., Fastook et al., 2009).

6.2. Estimating surface till thickness

While the flow patterns, stratigraphy, and broad-scale morphological characteristics of LDA and LVF north of Ismeniae Fossae are very similar to those described in other areas of the dichotomy boundary (Head et al., 2006a,b, 2009b; Levy et al., 2007; Kress et al., 2009; Morgan et al., 2009), there are some distinct differences that require explanation and should be a focus of comparisons between LDA and LVF across the northern mid-latitudes. The first characteristic is the relatively low population of ring-mold craters found on apron surfaces within the study region. Ring-mold craters consisting of 80% (Kress and Head, 2008) and ~64% (Ost-rach et al., 2008) of the total crater population (excluding flat-topped knobs) have been documented on LVF in Mamers Valles and on LDA surrounding isolated massifs in Deuteronilus Mensae. The presence of ring-mold craters was used in these studies to suggest that LDA and LVF consisted of nearly pure near-surface ice underlying a thin surface till layer at the time the craters were formed. Bowl-shaped craters were observed to have smaller average and maximum diameters than ring-mold craters, suggesting that bowl-shaped crater impacts did not completely penetrate the surface till of LDA and LVF and were not modified into ring-mold crater morphologies like larger impacts that were able to penetrate to the ice below. Bowl-shaped craters were therefore proposed to provide a means of estimating the thickness of the surface till layer of LDA and LVF. By assuming that excavation depth is 20% of the crater diameter (from the depth–diameter ratios of Kato et al. (1995)), a surface till thickness of ~15 m was estimated from the mean bowl-shaped crater diameter (~77 m) in Mamers Valles LVF (Kress and Head, 2008). Unlike these previous studies, we determined a much smaller crater population of ring-mold craters at only ~11% of all crater types (excluding flat-topped knobs) on all LDA and LVF groups mapped (Table 1). This low percentage is fairly consistent across the LDA and LVF groups, with percentages ranging from ~5% on mesa-cluster and crater interior LDA and LVF to ~15% and ~16% on plateau and dichotomy boundary LDA and LVF and isolated massif LDA, respectively (Table 1).

What may cause this low population of ring-mold craters? A simple answer might suggest that ice is not ubiquitous or is at greater depths beneath the surface till within LDA and LVF north of Ismeniae Fossae. The distinctly convex-up profiles and steep...
termini (Fig. 3) of almost all LDA suggest that ice is still largely present within the LDA, arguing against a highly deflated ice body or a pore-ice-talus composition for LDA and LVF (Li et al., 2005). A thicker till layer and greater ice depth is more likely. While the maximum diameter observed for bowl-shaped craters is larger than the maximum diameter of ring-mold craters (826 m versus 697 m), as a population, ring-mold crater diameters are generally larger than bowl-shaped crater diameters. On all mapped LDA and LVF surfaces (Fig. 5), the mean diameter of bowl-shaped craters is ~100 m, while the mean diameter of ring-mold craters is ~220 m (Table 1). The larger ring-mold crater diameters are also shown by the quantile statistics of the crater populations; the 75th and 95th percentiles for ring-mold craters are 265 m and 445 m, respectively, which are nearly a factor of two larger than the 75th and 95th percentiles for bowl-shaped craters at 122 m and 235 m. Based on these statistics we have some confidence in following the method of Kress and Head (2008), which results in a till thickness estimate of ~20 m from the mean bowl-shaped crater diameters observed in our study region. This estimate is ~5 m thicker than the 15 m till thickness estimate of Kress and Head (2008) for Mamers Valles. We also observe that the mean ring-mold crater diameter in our study region is about a factor of two larger than the mean ring-mold crater diameter of ~102 m documented in Mamers Valles. This is consistent with a thicker till layer

Fig. 18. Sample of apron textures from a variety of ring-mold crater densities (locations given in Fig. 17). (A) and (B) Common lobate debris apron textures observed in locations with the highest density of ring-mold craters (>0.05 per km²) (CTX images P17_007834_2259 and P17_007544_2247). These surfaces are dominated by an upper textured unit (unit T) comprised of tightly spaced knobs. Where unit T has been removed (B), a smooth, lower albedo unit (unit S) is found on the floors of pits within unit T. (C–F) Common lobate debris apron textures for aprons exhibiting low densities of ring-mold craters (zero to much less than 0.05 per km²) (CTX images P17_007834_2259, P18_007979_2264, and P17_007623_2271). These surfaces are highly pitted, forming irregular networks of ridges and depressions that disrupt unit T (“pits” in C–E). Some ridges occur as parallel sets (“ridges” in C) that occupy the floors of relatively low albedo furrows and are suggestive of aeolian modification of the LDA and LVF surface. Unit S is the dominant texture observed on some degraded LDA and LVF surfaces (E and F), with only patches of the upper textured unit preserved, suggesting a higher degree of removal of unit T from these LDA and LVF surfaces.
for LDA and LVF in our study region, as only large impacts would have been able to penetrate the protective till layer and form ring-mold crater morphologies.

An alternative explanation for the larger average ring-mold crater diameter in our study region is that the smallest ring-mold craters are being removed by erosion or other resurfacing processes. The roll-off observed in bowl-shaped crater populations <150 m in diameter (Fig. 14) suggest that removal of small craters is occurring faster than the craters are being created. The interpretation that at least some flat-topped knobs are remnant ring-mold craters is consistent with the surface erosion of ring-mold crater morphologies. If we assume that all flat-topped knobs originated as ring-mold craters and include the flat-topped knobs in the ring-mold crater population, ring-mold craters still only account for ~25% of the total crater population on all mapped aprons. This suggests that either ring-mold craters are being completely removed, or that they are not forming due to a deeper pure ice body or less ice-rich near-surface layers.

6.3. Degradation of LDA and LVF surfaces

Surficial crater density maps (Fig. 17) show that there is spatial heterogeneity in the distribution of ring-mold craters (RMC) on LDA and LVF surfaces. While there does not seem to be regular spatial patterns such as directional asymmetries in the spatial distribution of ring-mold craters, there are distinct regions where ring-mold crater densities are highest (>0.05 per km²) and others where few or no ring-mold craters are observed. Although the reason for this heterogeneity is not entirely clear, we speculate that it may be due to differences in degree of surface degradation. LDA and LVF surfaces with the highest ring-mold crater densities (Fig. 18A and B) are generally dominated by an upper textured unit (unit T) with small, tightly spaced knobs that are just visible at the resolution limit ofCTX images. This upper textured unit has been removed in places to expose a relatively smooth, lower albedo unit (unit S) (Fig. 18B). Unit S may be a relatively smooth, low albedo layer underlying the upper textured unit, or may be fines trapped in depressions formed by pitting of the upper textured unit. The area with the highest density of ring-mold craters (Fig. 16, box labeled Fig. 19) should be viewed with caution. While the crater morphologies observed here are similar to central mound and central pit ring-mold craters, they are more subdued and also occur in groups and chains that are uncommon for ring-mold craters (Fig. 19). Therefore, placed in context, their classification as ring-mold craters is somewhat ambiguous and may warrant exclusion from the ring-mold crater classification. Due to their small population (~10), small diameters (<250 m) and isolated occurrence, however, they are unlikely to significantly affect any crater statistics or analyses resulting from their inclusion as ring-mold craters and were thus not excluded from our crater statistics calculations.

LDA and LVF surfaces with the lowest ring-mold crater densities (<0.05 per km²) appear more degraded (Fig. 18C–F). Many of these surfaces are highly pitted, forming irregular networks of ridges and depressions that disrupt unit T and prominent flowline patterns (Fig. 18C–E). Some of these ridges occur as parallel sets that occupy the floors of relatively low albedo furrows (Fig. 18C) and are suggestive of aeolian modification of the LDA and LVF surface where fines are preferentially deposited in topographic lows and subsequently experience aeolian reworking. Unit S is the dominant texture observed on some LDA and LVF surfaces, with only patches of the upper textured unit preserved (Fig. 18E and F). The patchy occurrence of unit T and the dominance of unit S (as opposed to the pattern shown in Fig. 18B) suggest a higher degree of modification and/or removal of unit T from these LDA and LVF surfaces. Taken together, some of these textures may be interpreted as a degradational sequence, where an upper textured layer (unit T) erodes to produce relatively low albedo, smooth-floored pits (unit S) (Fig. 18B) that enlarge to produce a largely low-albedo surface with only patches of the upper textured unit remaining (Fig. 18E and F). This is consistent with the textures and process described by Mangold (2003), where aeolian deflation of a volatile-rich surficial mantling unit results in formation of the ridge and furrow texture of lobate debris aprons.

We also note that most of the mapped LDA and LVF surfaces do not exhibit the classic “brain terrain” surface texture observed at MOC resolution within LVF along the dichotomy boundary (Mangold, 2003; Levy et al., 2007, 2009). Observations of “brain terrain” textures in concentric crater fill, a class of features related to LDA and LVF, suggest that “brain terrain” is formed from a combined glacial and thermal contraction-cracking mechanism, which occurred during a peak glacial episode ~10–100 Ma (Levy et al., 2009). “Periglacial” formation of polygonally patterned ground in younger latitude-dependent mantle (LDM) that superposes concentric crater fill (Head et al., 2003), likely occurred through similar thermal contraction cracking and differential sublimation during the past ~1–2 Ma (Levy et al., 2009). The lack of readily-observed “brain terrain” and similar polygonally patterned textures within LDA and LVF in the study region suggests that either much modification of the apron surfaces has occurred within the past 10–100 Ma, or that thermal contraction and formation of polygonally patterned surfaces were not dominant processes within the study region. A closer examination of the occurrence of polygonal textures and the relationship between LDA and LVF “brain terrain” and latitude-dependent mantle should be a focus for determining the timescales of glacial and periglacial activity in the study region and throughout the mid-latitudes.

6.4. Potential effects of source material on the preservation and nature of glacial ice

We suggest that one of the reasons for the low ring-mold crater population and prevalence of degraded LDA and LVF textures...
observed within the Ismeniae Fossae study area may be due to the physical properties of the source material providing debris to LDA and LVF surfaces. Much of the plateau surfaces above LDA and LVF in the fretted terrain (Fig. 1) are likely to be of volcanic origin (e.g., McGill, 2000). In contrast, the unique setting of the study area along the rim of the Ismeniae Fossae impact basin (Fig. 2) (Schultz et al., 1982) may be providing highly brecciated and fragmented material from the cliffs to the till layers of the debris-covered glaciers. This finer, more comminuted debris (compared to more jointed and fractured blocks derived from lava flows) may be responsible for some of the variations in the development of sublimation lags and in the aeolian and related modification of these lags. Brecciated material is more easily dislodged than more competent volcanic rock, increasing both the degree of erosion occurring along the walls of escarpments and the thickness of the till layer formed on the glacier surface. The highly irregular perimeters and rounded edges of plateaus and the dichotomy boundary escarpment within the study region are consistent with a high degree of erosion occurring along these escarpments. Furthermore, the relatively low population of ring-mold craters and their relatively larger average diameter on apron surfaces supports a thicker surface till layer which would have shielded all but the largest impacts from the modifying effects of subsurface ice. Eroded brecciated material may have also quickly buried ice accumulated in alcoves, forming near-surface, interleaved layers of debris and ice. This “dirty ice” would have acted to reduce the modification effects associated with impacts into ice (Kress and Head, 2008), perhaps contributing to a reduction of the number of ring-mold craters produced. Dirty ice would have also facilitated the development of degraded, pitted textures (e.g., Fig. 18C–F), due to collapse associated with the shallow intra-lag sublimation of ice.

In summary, observations suggest that surface till characteristics may have been influential in producing the observed surface textures and crater distributions on LDA and LVF surfaces north of Ismeniae Fossae. Friable, brecciated material forming the escarpments of the northern rim of the Ismeniae Fossae impact basin may have facilitated erosion of these escarpments, producing irregular shaped escarpment walls and a thickened till layer on glacier surfaces. Increased erosion of this friable material from the escarpments may have also sequentially buried accumulated ice to produce shallow interleaved layers of debris and ice. A thickened supra-glacial lag consisting of erodable fines, and layers of “dirty” ice, may explain the lack of ring-mold crater morphologies in the study region and the observed degraded, pitted surface textures. Morphological observations made in tandem with shallow radar data from SHARAD and models examining the formation of sublimation lags for a variety of source materials (e.g., the Berlin Mars near Surface Thermal model (BMST), Helbert et al., 2009) will be useful in testing this hypothesis and evaluating how source material affects the evolution of ice within LDA and LVF in the mid-latitudes.

7. Conclusions

Analysis of criteria for the presence of debris-covered glaciers (e.g., Head et al., 2009b) and mapping of lineations within lobate debris aprons (LDA) and lineated valley fill (LVF) north of Ismeniae Fossae reveal flow patterns that: (1) emerge from bite-like alcoves on the walls of two large plateaus, the dichotomy boundary escarpment, and proximal massifs, (2) form highly integrated systems between adjacent escarpments and alcoves, (3) display down-gradient flow, (4) tighten and bend around topographic obstacles, and (5) open and broaden where topographically unconfined. The integration of these flow patterns over distances of tens of kilometers and the morphological similarities with terrestrial glacial landforms (e.g., Eyles, 1983; Benn et al., 2003; Head et al., 2009b) lend strong support to a debris-covered glacial origin for LDA and LVF in the study region.

Crater size-frequency distributions indicate that the most significant glacial episode may have been as young as 100 Ma (Late Amazonian). The occurrence of ring-mold crater morphologies (Kress and Head, 2008) also suggests that nearly pure, near-surface ice is present within some LDA and LVF north of Ismeniae Fossae, consistent with a debris-covered glacier interpretation. Smaller lobes superposed on the main LDA and LVF bodies likely represent a younger, less extensive glacial phase that was limited by the supply of snow and ice.

These results are consistent with previous studies along the dichotomy boundary (Head et al., 2006a,b, 2009b; Levy et al., 2007; Dickson et al., 2008; Kress et al., 2009; Morgan et al., 2009), which favor a debris-covered glacier origin for LDA and LVF. During changes from high obliquities of >40° to moderate obliquities of ~25–35°, snow and ice may have been remobilized from the poles or other sources and deposited in mid-latitude regions, accumulating on plateaus and in alcoves within topographic highs, compacting, and flowing down-gradient to form highly integrated glacial systems. Debris shed from the alcove and escarpment walls contributed to a supra-glacial till layer that thickened as the glacier ice ablated through sublimation. This thickened till layer likely retarded further sublimation, thus preserving the glacial ice to the present day. However, the relatively low percentages of ring-mold crater morphologies and the highly degraded textures observed for some portions of the LDA and LVF, suggest that differences in ice preservation and hence ice depth and content may exist within the study area. The different preservation potential of glacial ice below the till layer may be related to the specific location of this region at the rim crest of a 350 km diameter, highly degraded Noachian basin. In contrast to blocky debris that is most likely derived from mass wasting of ancient lava flows, fragmental megaregolith debris associated with the ancient Ismeniae Fossae impact basin may have provided a finer source material for glacial surface tills. The more friable and unconsolidated nature of the impact basin material would have favored more efficient mass wasting of escarpment walls, thicker sublimation lags, and interleaved primary ice in the lags. Assessing the differences between LDA and LVF textural patterns across the dichotomy boundary, as well as radar return signals from SHARAD (e.g., Holt et al., 2008; Plaut et al., 2009) will help to evaluate the preservation potential and quantity of ice likely preserved within these features in the northern mid-latitudes on Mars, and lead to an improved understanding of the full extent, character, and history of the Late Amazonian mid-latitude glaciation (e.g., Marchant and Head, 2009; Head and Marchant, 2009; Head et al., 2009b).

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