Lineated valley fill (LVF) and lobate debris aprons (LDA) in the Deuteronilus Mensae northern dichotomy boundary region, Mars: Constraints on the extent, age and episodicity of Amazonian glacial events

Gareth A. Morgan, James W. Head III, David R. Marchant

Article info
Abstract

In order to assess the nature, degradational processes and history of the dichotomy boundary on Mars, we conducted a detailed morphological analysis of a 70,000 km² region of its northern portion (north-central Deuteronilus Mensae, south of Lyot, in the vicinity of Sinton Crater). This region is characterized by the distinctive sinuous ~2 km-high plateau scarp boundary, outlying massifs to the north, and extensive fretted valleys dissecting the plateau to the south. These features represent the first-order modification and retreat of the dichotomy boundary, and are further modified by processes that form lineated valley fill (LVF) in the fretted valleys, and lobate debris aprons (LDA) along the dichotomy scarp and surrounding the outlying massifs. We use new high-resolution image and topography data to examine the nature and origin of LVF and LDA and to investigate the climatic and accompanying degradational history of the escarpment. On the basis of our analysis, we conclude that: (1) LVF and LDA deposits within the study region are comprised of the same material, show integrated flow patterns, and originate as debris-covered valley glaciers; a significant amount of ice (hundreds of meters) is likely to remain today beneath a thin cover of sublimation till. (2) 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; this is supported by similar deposits within many other areas across the dichotomy boundary. (3) The timing of the most recent large-scale activity of the LDA/LVF in this area is about 100–500 million years ago, similar to ages reported elsewhere along the dichotomy boundary. (4) There is evidence for a secondary, but significantly limited phase of glaciation; the deposits of which are limited to the vicinity of the alcoves; similar later phases have also been reported elsewhere along the dichotomy boundary. (5) Modification of the fretted valleys of the dichotomy boundary has been substantial locally, but we find no evidence that the Amazonian glacial epochs caused retreat of the dichotomy boundary of the scale of tens to hundreds of kilometers. Our findings support the results of an analysis just to the east of the study region and of studies carried out elsewhere along the dichotomy boundary that find further evidence for the remnants of debris-covered glaciers and extensive valley glacial land systems.

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1. Introduction

The martian dichotomy boundary divides the lowland northern plains from the heavily cratered southern highlands, and is marked by a near-global escarpment that exhibits several kilometers of relief (Fig. 1). The origin of the northern plains and the formation and evolution of this escarpment remain among the most enigmatic chapters in the geological history of the planet (Watters and McGovern, 2006). The highlands flanking the escarpment are considered to be typical of the material that comprise Noachis Terra to the south and are interpreted to be composed of both sediments and volcanic material that has been mixed and reworked by impacts (Tanaka et al., 2005). The northern lowlands have served as a repository for both sediments shed from the surrounding ancient highlands and for volcanic flows and deposits from sources within and near the lowlands (Tanaka and Scott, 1987; Tanaka et al., 2005). The derivation of hypotheses and models to explain the boundary relies on successfully constraining the original position and scale of the escarpment at the time of its formation. This can only be achieved with a comprehensive understanding of the degradation processes operating along the boundary and by making assessments of the level of modification it has undergone, permitting the lateral extent of retreat over geologic time to be mapped and identified (Watters and McGovern, 2006).
The most topographically distinctive region of the dichotomy boundary is located along its northernmost margins (30–50° N) at Deuteronilus–Protonilus Mensae (Fig. 1). This area is dominated by fretted terrain that is defined by sinuous and linear valleys that extend from the southern highlands and widen into the northern plains, isolating plateaus and mesas that become progressively smaller to the north (Sharp, 1973). The modification of this portion of the boundary has in part been attributed to two distinct degradational features; Lobate Debris Aprons (LDA) that originate from and surround isolated mesas and the escarpment flanks, and Lineated Valley Fill (LVF) which is found to line the floors of the fretted valleys (Squyres, 1978). Three general hypotheses have been proposed for the origin of LVF and LDA: (1) Mobilization of ancient ice-rich highland regolith, in part helping to create the fretted valleys, and then finally leading to the formation of LDA-like features (Lucchitta, 1984; Carr, 1996); (2) Vapor diffusion of atmospheric water vapor into talus, providing a lubrication mechanism, and permitting viscous flow along flanks of valley walls and massif margins, has also been proposed, although the exact nature of the amount of ice has been highly debated (e.g. Carr, 1996; Mangold, 2003); (3) Following earlier suggestions (Lucchitta, 1984), more recent studies have hypothesized that LDA and LVF are largely glacial in origin (Head and Marchant, 2006a, 2006b; Head et al., 2006a, 2006b, Kress et al., 2006), a hypothesis supported by observations from research on debris-covered glaciers in terrestrial analog sites, especially the Antarctic Dry Valleys (Marchant and Head, 2004, 2007). In this scenario, LVF and LDA represent debris-covered glaciers that formed in an earlier period of the history of Mars when climate change caused snow and ice to accumulate preferentially in these regions. According to this model, regional snow and ice accumulation caused glacial flow in valleys (LVF) and at the margins of massifs (LDA), and debris from adjacent massifs and valley walls created a cover of sublimation till that protected the buried ice from sublimation when climate conditions changed. In contrast to the ancient ground ice and viscous flow hypotheses, this scenario predicts significant amounts of primary ice in LVF/LDA formation, with much of it remaining today (Marchant and Head, 2007; Dickson et al., 2008).

Despite much recent progress, several uncertainties remain in the understanding of the degradational history of the dichotomy boundary and the processes that form the LVF and LDA: (1) What is the proportion of ice and debris involved in the initial stages of formation of LDA and LVF and how much remains today? (2) What were the lateral and aerial extent of the conditions that produced the LDA–LVF at the dichotomy boundary? (3) What was the timing and duration of these periods of accumulation and flow and how do these help distinguish models of formation? (4) What were the mechanisms for accumulation of ice and snow that might have caused these features and the general link to martian paleoclimate conditions? and (5) Is there evidence for multiple periods when LVF and LDA may have occurred in these regions?

In this study we concentrated our efforts on the fretted valleys surrounding the 63 km diameter Sinton impact crater formed on a plateau on the northern edge of the dichotomy boundary at 32° E, 39° N (Fig. 2). This region was chosen because it represents a high-latitude portion of the dichotomy boundary, it includes examples of both LVF and LDA, it contains several different orientations of fretted valleys, it has abundant LDA-containing massifs, and it is adjacent to a 30,000 km² region containing a regionally integrated system of LVF (Head et al., 2006b). Through assessment of an array of spacecraft data including MOLA altimetry, HRSC DTMs, and THEMIS, HRSC, MOC, CTX and HiRISE high-resolution images, we analyzed LVF and LDA within the region in detail to address the questions outlined above.

2. The evolution of theories of LDA/LVF generation and critical observations

Early hypotheses pertaining to the processes responsible for the LDA called upon the actions of frost creep or gelifluction, operating on ancient ice-rich, permafrost-like regolith during earlier periods of martian history when increased geothermal gradients caused mobilization and flow (Carr and Schaber, 1977). Observations supporting this hypothesis would be: (1) a relatively ancient age of
Fig. 2. (a) Oblique view (facing directly to the north) of the study region represented in a MOLA DEM. We focus on the plateau in the upper right portion of the image containing the 60 km diameter Sinton impact crater and the adjacent valleys. At MOLA resolution, Lineated Valley Fill (LVF) appears as a smooth deposit and is observable throughout the valleys surrounding the main plateau. (b) Map of the study area highlighting the extent of the LVF and Lobate Debris Aprons (LDA) systems within the region. The dashed white line indicates the area containing the LVF and LDA deposits, which are found above an elevation of −3200 m. Boxes indicate the locations of images in Figs. 4–7 and 15. The dashed lines correspond to topographic profiles in Fig. 4. The map consists of a portion of HRSC image 1589, overlain by MOLA topographic data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
LDA and LVF, (2) distinct continuity between plateaus undergoing mobilization and the resulting lobes, (3) evidence for associated melting and water flow, and (4) modest amounts of ice involved (pore ice and secondary ice). As new data became available regarding the thickness of these features (0.5–>1 km), their apparent youthfulness, and the inability of the current/recent climate to permit thawing to significant depths, frost creep was considered an unlikely candidate for such large landforms (Squyres, 1978). Squyres (1978) proposed that the LDA were comparable to terrestrial rock glaciers, in that they were mass wasting products (talus piles) lubricated by the accumulation of ice in pore spaces permitting them to flow. Snow (and snowmelt) is typically the source of ice for such landforms on Earth, but diffusion of atmospheric water vapor was considered to be a more likely source for the ice in the martian case (Squyres, 1978). Considering the morphological similarity between LDA and lineated valley fill (LVF), LVF was assumed to be the result of two or more LDA flowing from opposing valley walls, and converging in the valley center, completely covering the valley floors (Squyres, 1978). LVF is characterized by along-valley lineations composed of ridges and grooves that had been identified in the original Viking images and were subsequently explained by Squyres (1978) to be the manifestation of compressional forces as the LDA converged within the middle of the valley. Observations supporting this hypothesis would be:

1. Localized patterns of LDA convergence to produce LVF,
2. Minimum down-valley flow,
3. Morphometric parameters indicative of pore ice and small amounts of secondary ice, rather than large ice volumes (e.g. cross sectional profiles indicative of viscous flow associated with high debris content rather than ice flow), and

In contrast to these interpretations, Lucchitta (1984) initially noted a down-valley flow component evident in some examples of LVF, and compared these patterns to those seen in Antarctic glaciers. On the basis of increased knowledge of Antarctic analogs (see Marchant and Head, 2007; this hypothesis has recently been further developed by Head et al., 2006a, 2006b) who argue that LDA represent debris-covered glaciers and that LVF represents the remnants of debris covered valley glacial landsystems (Marchant and Head, 2007). In this scenario, regional ice and snow accumulation results in plateau icefields and valley glaciers that converge and flow downslope in fretted valleys to create regional glacial landsystems; the current deposits represent the remnants of previously much more extensive glacial landsystems (Dickson et al., 2008), with remnant ice currently protected by a cover of sublimation till derived from adjacent scarps. LDA represent localized debris-covered glacial remnants surrounding isolated mas-
sifs. GCMs developed for Mars have demonstrated that substantial snow and ice can be deposited along the dichotomy due to the redistribution of volatiles during high obliquities (Madeleine et al., 2007). Simulations of the orbital history of the Solar System demonstrate that Mars has undergone significant variations in obliquity throughout its history which has included excursions greater than 80° (Laskar et al., 2004). Observations supporting the glacial hypothesis would be: (1) cirque and valley glaciers in the proximal areas of LVF, (2) convergence and flow to create regional integrated patterns of LVF, (3) morphometric parameters indicative of large ice volumes, (4) down-valley topographic gradients in fretted valleys indicative of regional, not local, flow.

3. Methodology and approaches to studying LVF/LDA

3.1. The study region

The study region is centered at 30° E, 40° N, within Deuteronilus–Protonilus Mensae. This location was selected because it was situated between two previously studied regions, one to the west (Head et al., 2006a) and one to the east (Head et al., 2006b), and thus enabled us to extend the analysis of the most prominent portion of the dichotomy boundary. The LVF system within the study area extends throughout a region of 70,000 km², and is best expressed within a ~15 km wide valley formed between the main plateau on which Sinton crater is situated and the cratered uplands (Fig. 2). LVF is also present within connecting smaller tributary fretted valleys and breached craters that are located to the south of the main plateau (Fig. 2). Large areas of LDA are present within the study region, predominantly along the northern flanks of the main plateau and around the walls of the 130 km basin located in the western part of the study region. Fig. 3 illustrates the nature of the morphology of LDA, which consist of low slope angles (~1°) along the main body of the aprons, steepening to <5° towards the terminus (identifiable by the yellow and red shades and highlighted by the arrows in Fig. 3), forming a convex cross-sectional profile (see Fig. 4). Such a profile is consistent with LDA located across the northern dichotomy boundary region (Squyres, 1978; Li et al., 2005).

3.2. Data sets and analysis

The investigation was conducted through the compilation of a Geographical Information System (GIS) database comprised of the relevant martian data sets for the study region. The database consisted of: (i) topographic data from both 128 pixel/degree gridded Mars Orbiter Laser Altimeter (MOLA) data and High Resolution Stereo Camera (HRSC) stereo data (200 m/pixel); (ii) visible image datasets including: (1) HRSC images (18 m/pixel), (2) Thermal EMission Imaging System (THEMIS) visible images (19 m/pixel), (3) Mars Orbital Camera (MOC) narrow angle images (1.5–12 m/pixel), (4) Context Imager (CTX) images (8 m/pixel) and (5) HiRISE images (0.3 m/pixel); and (iii) thermal infrared data from daytime and nighttime THEMIS infrared images (band 9, 100 m/pixel). ESRI’s ArcMap (9.2) provided the GIS platform, which in addition to dataset management was also utilized to produce slope maps and topographic profiles from the interpolated MOLA data and conduct crater counts, all of which contributed to the research process.

4. Observations and interpretations of LDA/LVF in the study region

4.1. Alcoves and tributary valleys and the source of LVF/LDA

We found that alcoves and tributary valleys along the fretted valley margins and the scarp margin were a prevalent feature
may have been capable of providing the necessary shelter for the accumulation of ice during the later periods of glacial activity associated with the most recent Amazonian ice ages (e.g. Head et al., 2006b). Therefore, it may be difficult to ascertain the exact contribution that processes related to glacial activity alone have provided to the erosion of the dichotomy boundary. Nevertheless, the very large number of modified alcoves and enclaves which occupy almost every kilometer of the plateau flanks, and those of the surrounding mesas, is testimony to the level of local erosion that the dichotomy boundary has experienced due to apparent glacial-associated processes.

Longitudinal lineations consisting of orientated ridges run the length of the majority of individual LVF lobes and are aligned with the prominent direction of flow (Figs. 7–10). At the mouth of the alcove in Fig. 8, the lineations are observed to form chevron patterns in the downslope directions. On terrestrial glaciers, such ‘zigzag’ patterns are observed as contorted medial moraines and supraglacial debris resulting from folds developing in the ice due to compressional and shear forces. In the case of Fig. 8, such folding can be explained by comparable compressional stresses acting on the body of the LVF. In the complex alcoves, materials within the individual enclaves merge with the LVF within the main trunk to form lobes that become wider as a function of distance downslope. A particularly good example of the interaction of such material is seen in Fig. 9, where two separate lobes develop and converge together at the opening of the alcove system. This is made particularly apparent by the individual longitudinal lineations that run along the central portions of LVF within the enclaves. These merge together at the mouth of the alcove system and form a single series of parallel ridges (Fig. 9) that are similar to the broad ridges present on the surface of LVF lobes emanating from simple alcove systems (Fig. 10).

The point of contact between lobes emanating from the alcoves and the major LVF and LDA systems is one of convergence, as one deposit merges into the other, further suggesting that they all consist of the same material, and reflect integrated flow (Fig. 7). In some circumstances concentric ridges perpendicular to the direction of flow can be observed in the LDA downslope of the emerging lobe (Fig. 9). As the lobe material becomes increasingly integrated within the LDA in the downslope direction, the ridges become progressively less defined to the point that they can no longer be identified. This occurs at a distance of ∼10 km from the alcove mouth. Such morphology is also apparent with integrated debris covered glacial systems on Earth, such as Beacon Valley in the McMurdo Dry Valleys of Antarctic (Fig. 9), an important analog for geological processes on Mars (Marchant and Head, 2007; Levy et al., 2006; Shean et al., 2007). For example, a similar relationship is seen where the Mullins Valley debris-covered glacier integrates with debris-covered ice within central Beacon Valley (Fig. 9). Concentric ridges resulting from compression associated with the advance of Mullins are highlighted by the deposition of windblown snow within the troughs between the undulations that occur down-slope of the entrance of Mullins valley.

These relationships strongly suggest that LVF and LDA systems originated from the same source regions and environments (alcoves and tributary valleys), and grew over time until enough material had emerged from the alcoves to generate the LVF that fills the fretted valleys. Such observations and interpretations are consistent with the investigations carried out to the east by Head et al. (2006b) and other localities across the dichotomy boundary, including Protonilus Mensae (Levy et al., 2007), Mamers Valles (Kress et al., 2008) and Coloe Fossae (Dickson et al., 2008). Together, these observations are consistent with the debris-covered glacial model of LVF/LDA emplacement. The recent acquisition of SHARAD (SHALLOW RADar) subsurface radar data in an extensive area of LVF and LDA (Head et al., 2006a, 2006b) strongly suggests that almost
Fig. 6. Examples of patterns of divergence and convergence visible within the surface of the LVF systems mapped in Fig. 5. (a) Convergence of LDA between a gap within a topographic ridge (large arrow) forming a 3 km wide lobe of material on the downslope side. The main branch of LDA is fed by small lobes (small arrows) emanating from several kilometer wide alcoves along the northern flanks of the plateau. THEMIS image V12506004. (b) Convergence and integration of flow between a 10 km wide mesa and the main plateau (highlighted by large arrow). Small lobes can be seen flowing from the flanks of the mesa (small arrows). THEMIS image V03282003. (c) Divergence of flow around a 5 km mesa. The flow originates from small lobes within alcoves to the west of the image (small arrows) and flows out the north and east around isolated mesas. CTX image P13_006239_2240.
pure water ice underlies a thin debris-rich surface (Plaut et al., 2008). This adds further support to the interpretation that the two-landform types are the product of debris-covered glacial activity.

4.2. Evidence for integrated systems of LVF/LDA

From observing the apparent flow patterns in HRSC, THEMIS and MOC high-resolution images throughout the entire study region (Fig. 5), it has been possible to map integrated systems of LVF and LDA across this area of the dichotomy boundary. Such mapping techniques have already been applied successfully to the LVF systems to the east of the study region (Head et al., 2006b). This mapping revealed an integrated flow system extending in excess of 200 km in length, covering an area of \( \sim 30,000 \text{ km}^2 \). In our study area, integrated LVF systems are especially apparent within the LVF and LDA, surrounding the western extent of the main plateau (Fig. 5).

The convergence of surface lineations reveal the constriction of the flow of LVF. A prominent example of this is seen in Fig. 6a where the downslope flow of LDA has been constricted through the opening of a topographic ridge to produce a bulbous lobe of LDA \( \sim 5 \text{ km} \) wide on the downslope side. Flow constrictions are also apparent between broader-scale obstacles, as can be seen by the relatively more subtle convergence surface features between the mesa and the western edge of the main plateau (Fig. 6b). In contrast to this, flow also diverges around obstacles such as mesas (Fig. 5).

The integrated nature of the LVF/LDA systems within the study area is morphologically similar to terrestrial networks of connected valley glaciers that form almost web-like patterns within regions of high relief, that are too dissected to support an ice cap (e.g. the current valley glacial landsystems of the McMurdo Dry Valleys, Antarctica, Marchant and Head, 2006). These terrestrial systems have been called *transection glaciers* by Benn and Evans (1998), and can grow sufficiently large that they can overcome local drainage configurations. Evidence of flow is observed from opposing ends of valleys that have high stands at points midway along the center of the valley. This is the case in the large valley to the south of the main plateau in the study area, in which the highest elevation of its floor is in the center, as opposed to one of its ends (Fig. 2). The material flowing from the alcoves into this valley curve away from the point of maximum elevation (Fig. 5), supporting the interpretation that along-valley flow is occurring at either end of the valley. Squyres (1978) cited the prevalence of lineated valleys across the entire dichotomy boundary area as evidence that LVF formed from simple convergence of flow from both sides of the valley, with minimal to no lateral flow. Identification of the alcoves as sources of LVF, however, suggests that glacial processes can indeed explain such situations.

MOLA-derived, along-slope profiles of the LVF and LDA systems (Fig. 4) reveal that all of the deposits correspond to similar lobate cross-sections which are characteristic of LVF/LDA bodies throughout the region (Mangold and Allemand, 2001; Turtle et al., 2003; Li et al., 2005). The LVF slope within the valley to the south of
the main plateau tilts towards the west at an angle of $\sim 1^\circ$, but steepens rapidly to $> 4^\circ$ where the LVF terminates into a large basin (Fig. 2), producing a convex-up profile with a relatively steep front that is reminiscent of the fronts of many terrestrial glaciers (Figs. 3 and 4). Similar profiles are also observed in the LDAs that emanate away from the northwestern portion of plateau and into the northern plains (Fig. 4). Investigations of the profiles of other LDAs across the dichotomy boundary compare well to plastic models of deformation indicative of the presence of high concentrations of ice (Mangold and Allemand, 2001; Turtle et al., 2003; Li et al., 2005). The north-south trending profiles, which cross LVF/LDA along the western portion of the study region, also reveal that the small mesas to the north have similar surface elevations to each other and to the main plateau. Such topographic traits were observed in the area immediately to the east (Head et al., 2006b). Such profiles are consistent with glacial erosion alongside mesas, reducing their overall volume but leaving their summit elevations intact; over time this has resulted in the gradual ‘mesa-ization’ (Head et al., 2006b) of the northern margin of the dichotomy boundary.

4.3. Evidence for post-flow modification of the LVF/LDA systems

Most workers agree that the fundamental flow-like patterns observed in the LDA/LVF at Viking, THEMIS VIS and HRSC resolution reflect primary surface textures that date from the emplacement of the deposits and are caused by their lateral motion and flow (e.g., Mangold, 2003; Head et al., 2006a, 2006b). Studies conducted using the highest resolution data sets (MOC and more recently CTX and HiRISE) however, have revealed the LVF/LDA surface environment to be comprised of a collection of complex textures, that have in part been formed by more recent modification (e.g. Mangold, 2003; Levy et al., 2009). In a review of observations made by the Mars Global Surveyor spacecraft of the dichotomy boundary, Carr (2001) utilizing high resolution MOC images was able to further characterize the fretted terrain environment and found it to consist of three main components: (1) a steep upper slope, where bedrock may be visible, (2) intermediate units (IU) which appear smooth, and may have faint lineations in the downslope direction, and (3) debris aprons (LDA) or lineated valley fill (LVF) at lower elevations and on the valley floor. Further studies at MOC resolution of the surface of LVF/LDA deposits revealed that a large number of surface units are comprised of complex terrains consisting of pits and buttes. The occurrence of such units (also termed ‘brain terrain’; Noa Dobrea et al., 2007) across the surface of the LDA/LVF has been attributed to the significant loss of ice through sublimation (Mangold, 2003; Levy et al., 2009).

The three components of the fretted terrain environment characterized by Carr (2001) are clearly present within the LVF/LDA environments of the study region (Figs. 11 and 12). Through the utilization of more recent data sets along with MOC images we have further investigated the surface textures present on these components within the study area. We find that distinctions between the main components can be made based on differences between their thermal properties in addition to the morphological differences reported by Carr (2001). Below we report on our findings.
Intermediate Units (IU) can be observed between the steep upper slopes and the rough textual (i.e., brain terrain) portions of both LDA and LVF deposits across the study region (e.g., see Figs. 11 and 12). IU also comprise the surface of the LVF lobes emanating from the alcoves. The units are typically ~2 km wide and can extend continuously for up to several hundred kilometers along the base of plateau slopes and completely surround the flanks of mesas (Fig. 11). They appear as a region of relatively smooth terrain with respect to the rougher LDA/LVF surfaces at all spatial scales from HRSC (~18 m/pixel) to HiRISE (sub-meter) resolutions (Fig. 12). IU are also evident in THEMIS IR mosaics of the study area (Fig. 11), and appear relatively bright (higher temperature) compared to the adjacent LVF unit and plateau surface in both the daytime and nighttime data sets. In order to explain the higher nighttime temperatures we suggest that the IU have a higher thermal inertia than the surrounding units (Christensen et al., 2003). This in turn is a proxy for grain size of the surficial deposits, suggesting that the IU consist of coarser material than that of the adjacent LVF (although it is worth noting that the reduction in sky exposure caused by the adjacent steep slopes may insulate the unit from radiative loss (Hecht, 2002), and thus contribute to higher nighttime temperatures). Nevertheless, the direct correlation between the temperature signal and the distinct morphology of the IU in the image data sets (Fig. 11) suggests that topography alone does not fully account for the higher nighttime temperatures.

Therefore, following Carr (2001), we interpret the IU to represent a relatively recent debris cover, the source of which is likely to be the adjacent higher exposed slopes (the steep upper slope unit of Carr, 2001). Boulders ~1 m in diameter can be identified along the interior slopes of alcoves and the flanks of the main plateau (Fig. 13) forming screes which is interpreted to be the product of erosion along the slope. The slopes also appear very bright in the nighttime IR (Fig. 11), a finding that is consistent with other steep slopes elsewhere on Mars (Christensen et al., 2003). This is interpreted to be caused by the concentration of coarse material as a result of sub-areal processes operating on slopes close to the angle of repose (Christensen et al., 2003). Evidence for mass wasting along the slopes in the study area exists in the form of spur and gully erosion along the plateau/alcove flanks that has produced highly linear troughs a few meters across (Fig. 13). We find no evidence for the involvement of liquid water in the formation of these features (as has been implied for larger gully forms; Malin and Edgett, 2000), and interpret them to represent critical slope failure and the generation of dry debris slides. The supply of such debris to the lower portion of the slopes could thus account for the formation of the IU. The LVF/LDA surfaces in contrast appear to be comprised of finer, reworked debris derived from sublimation of the underlying ice (Mangold, 2003; Levy et al., 2009). These may also be covered by a significant amount of eolian dust that has become trapped within the pits along the surface, which together could account for their lower thermal inertia.

Our findings suggest that the LDA/LVF deposits within the study area have undergone modification since their emplacement. This has been in the form of both potential ice loss from sublimation related process to generate the pit and butte texture.
Fig. 10. Direction of flow of material within the main trunk valley LVF deposits inferred from the integration with LVF material emanating from an alcove within the southern portion of the main valley. At the point where the lobe merges with the main body of the LVF, the lineations along the surface curve to the southeast, despite the fact that the alcove is oriented in a southwesterly direction. This indicates that at the time that the LVF deposits were formed, the main trunk of LVF within the southern valley flowed in an easterly direction. This demonstrates how LVF accumulating within an alcove could have supplied main trunk valleys with ice-rich material when the deposits were active. At this spatial resolution (3 m/pixel) such lineations appear as accumulations of ridges and knobs (depicted as horizontal lines in (b)) that are interpreted to be the result of sublimation of ice from within the LVF deposit (e.g. Mangold, 2003). MOC image E1900479.

of their surfaces (which has been described by Mangold, 2003; Levy et al., 2009) and through the formation of IU along their margins with the surrounding valley flanks. This demonstrates that for the majority of the surface impact craters, the original features associated with the last phase of activity are only preserved at longer wavelengths (≤10 m scale). Hence the current state of the LDA/LVF deposits is best described as the terminal remnant of previous activity when viscous flow last occurred (see Dickson et al., 2008).

5. Age estimates of LVF/LDA emplacement

Due to the wide distribution and integrated nature of the LDA/LVF deposits, their surfaces provide suitable areas on which to conduct crater size frequency distribution surveys and thus place constraints on the age of the deposits. The LVF/LDA deposits within the study region display impact craters with a similar range of degradation to that observed by Mangold (2003) within LDA deposits elsewhere across the northern dichotomy boundary. The study area displays crater morphologies which vary from fresh, circular depressions to flat ‘oyster shell’ and heavily subdued ‘ghost’ craters (Mangold, 2003). Mangold (2003) attributed the degradation of these craters to enhanced sublimation, which has also been responsible for the pitted texture present on the surface of LVF/LDA. More recent analysis of these small scale (<1 km) craters on the surface of LVF/LDA deposits have found further evidence to suggest that impacts occurred into ice rich targets. McConnell et al. (2006) used numerical and physical models to demonstrate the formation of central mounds due to ice rich targets. Kress et al. (2008) noted a size distinction between smaller circular bowl-shaped craters and larger ‘ring mold’ craters, which they attribute to the difference between smaller impacts that occurred purely within a thin surface debris layer, and larger impacts that were large enough to pierce this upper layer and excavate ice-rich material below. The wide range in crater morphology attributed to impacts into ice rich targets and their subsequent modification caused by enhanced sublimation means that crater counts will provide a minimum age for the emplacement of the LDA/LVF units.

The largest continuous extent of LVF/LDA in the study region is present within the extensive elongated fretted valley to the south of the main plateau. Due to the distinctions between the intermediate units and the surface of the LVF deposits that were discussed earlier, we focused our crater counting on the LVF units that provide a continuous area extending for ~190 km in the main southern valley. All identifiable craters larger than 100 m were counted regardless of their morphology or apparent level of degradation. One HRSC image (orbit 1589) was used to maintain a consistent resolution and image quality over the entire count area. Isochrons plotted according to the Hartmann (2005) system were used and compared to our results (Fig. 14). These show good agreement with the 100 Ma isochron, though slightly offset to the right for craters larger than 250 m. This indicates a surface age for the LVF within the Late Amazonian (>100 Ma–500 Ma), a result that is consistent with other published results of LVF/LDA surface ages (e.g. Mangold, 2003). For craters smaller than 250 m, there is a noticeable downturn in the crater distribution, suggesting a period of resurfacing. This further supports the occurrence of mantling and degradation due to sublimation operating along the surface of the LVF/LDA deposits (Levy et al., 2009). The absence of the smallest craters following any of the isochrons indicates that the degradation process may still be active or at least was active until very recently (see also Mangold, 2003), which is consistent with the current instability of ice on the surface of Mars at these latitudes.
6. Evidence for the previous extent and thickness of LVF

The acquisition of very high-resolution images (MOC, CTX, HiRISE) provides an opportunity to search for evidence for the previous distribution of LDA and LVF (on alcove walls, as high stands and trimlines, and evidence for ice on adjacent plateaus, etc.). The instability of water ice throughout the martian year at latitudes where LVF deposits at present (Farmer and Doms, 1979; Mellon and Jakosky, 1995) suggests that volatile-rich landforms at these latitudes will lose ice to the atmosphere over time by vapor diffusion and sublimation. As was previously discussed, evidence for significant sublimation is apparent on the surface of LVF deposits, as they exhibit a pit and butte/brain terrain texture, the

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**Fig. 11.** (a) HRSC image of the study area highlighting the IU. (b) Mosaic of nighttime THEMIS infrared images of the southern portion of the plateau. The mosaic has been normalized to account for the different times of night at which the individual images were taken. Intermediate Units (IU) present along the flanks of the plateau and within the alcoves themselves can be seen as regions of brighter pixels corresponding to relatively higher temperatures, which in turn is most likely correlated with a relatively high thermal inertia. Thus we interpret the IU to represent a debris cover of relatively coarse material compared to that which comprises the surface of the main body of LVF. (a) The location of Figs. 12 and 13 are highlighted. Image is a subset of HRSC 1589.

**Fig. 12.** MOC image of three main components of the fretted terrain environment identified by Carr (2001): (1) a steep upper slope, where bedrock may be visible, (2) intermediate units (IU) which appear smooth, and (3) LDA or LVF (which in the case of this image is LVF). The surface of the LVF is comprised of pits and buttes. The context for the figure is provided in Fig. 11. MOC image: R1201629.

**Fig. 13.** High-resolution (~0.3 m/pixel) view of the main plateau flanks adjacent to an alcove containing a source lobe of LVF (see Fig. 9). Scree, containing boulders (meters in diameter), is resolvable along the plateau flanks and is a plausible supply of debris to the IU along the surface of LVF/LDA deposits surrounding the plateau. Erosional features in the form of spur and gully morphology are testimony to the occurrence of mass wasting along the slopes. The context for the image is displayed in Fig. 9a and Fig. 11. Image is a subset of HiRISE image PSP_006806_2215.
The debris-covered glacial model for LVF formation interprets the presence of the debris cover as resulting from the production of a surface lag formed on the deposits by the concentration of debris material through the sublimation of ice. This process results in a sublimation till, similar to that seen on debris-covered glaciers in the Antarctic Dry Valleys (Marchant and Head, 2003, 2007). The formation of the sublimation till serves to inhibit further loss of ice (Head et al., 2006a). In addition, during the transition from active glaciaion to the currently observed state of preservation of the deposits, ice in the accumulation zones will change balance from net annual ice accumulation to net annual ice loss. This means that glacial flow will continue for some time after the change in this critical balance, but that the glacial system will undergo both lateral retreat and vertical downwasting. By extension, this suggests that significant ice has been lost from LVF, and indeed that entire glaciers might have been lost in areas where the debris supply was limited and thus prevented the formation of protective sublimation tills. Utilizing HiRISE data, Dickson et al. (2008) found evidence for the occurrence of linear ridges that run along the internal walls of alcoves that hosted individual lobes of LVF. These features were interpreted to be lateral moraines that were deposited when the LVF deposits were at least 900 m higher than at present. We also investigated the available HiRISE coverage of the study region in order to search for the presence of similar landforms.

The highest resolution views (25 cm/pixel) of the flanks of the main plateau reveal linear features that are orientated parallel to the slope contours (Fig. 15). These linear features are ~10 m wide and extend (sometimes discontinuously) for 100 s of meters. Shadows cast by these lineations indicate that they are positive features. The ridges are too small to be resolved in either MOLA or HRSC DTM images, although the shadows they cast indicate that they are of the order of several meters high. The ridge-like nature of these landforms argues against an origin as exposed bedrock and suggest that they may be depositional features. Boulders (about a meter in diameter) are present on the flanks of the ridges and form scree (Fig. 15), which may have originated from the degradation of the ridges. If this interpretation is correct, it further suggests that the ridges are comprised of largely unconsolidated material, including boulder-sized debris.

On the basis of the morphology and orientation of these features, we interpret them to be lateral moraines that were deposited along the margin of the ice when the LVF material was at a higher elevation, and occupied a greater portion of the valleys and alcoves. The difference in elevation between the current surface of the LVF and the highest ridge is 800 m, thus suggesting that at least this amount of ice has been lost from the current LVF deposits. This is consistent with the findings of Dickson et al. (2008), who showed evidence for loss of over 900 m of ice in LVF along the dichotomy boundary. Terrestrial lateral moraines require a supply of debris that is usually produced by the mass wasting of slope material above the ice (similar to what was observed and discussed in Section 4.3, see Fig. 13), or transported laterally along the margins from debris forming in the accumulation zone. Therefore, if this interpretation is correct, this observation provides a minimum estimate of the previous thickness of the LVF deposits, as ice above this elevation would have been above sources of debris that are required to form the lateral moraines.

7. Evidence of multiple phases of LVF emplacement

Within the overall pattern of integration present in the LVF and LDA systems in the study region (Fig. 5), there is a distinct group of small lobate flow units that appear at THEMIS resolution to be superimposed on, rather than coalescing with, the surrounding larger scale LVF/LDA systems (Figs. 9 and 16). These flow units are located along the southwestern flanks of the main plateau and are associated with individual source alcoves; they appear similar in both scale and morphology to the LVF lobes that have been identified emerging from other alcoves along the main plateau. As was observed with the LVF lobes (Figs. 7–10), the superimposed flow units display surface lineations, including longitudinal ridges that are oriented along the center of the deposit in the downslope direction (Fig. 16), producing patterns of convergence between topographic obstacles indicative of terrestrial debris-covered glacial flow (Head et al., 2006b). The flow units terminate downslope of the mouths of their source alcoves in the form of expanded lobes, further supporting the argument that these features are comprised of ice-rich materials. In contrast to the other LVF lobe features (Figs. 7–10), the snouts of the superimposed units remain completely distinct from the main LDA bodies onto which they emerge, with no evidence of merging, blending and integration at the point of contact between the two units, or any other form of disturbance within the main LDA body downslope of the contact area (e.g. compare Fig. 9 with Fig. 16).

This suggests that the superimposed features are stratigraphically separate units that overlie, and are thus younger than the surrounding main trunk LDA systems. If this is indeed the case, it implies that the units were emplaced and active after the cessation of flow within the main integrated bodies LVF/LDA. Similar features have also been identified within the LVF systems present in both Nilosyrtis Mensae (Levy et al., 2007) and the Protonilus Mensae-Coloe Fossae region (Dickson et al., 2008) of the dichotomy boundary. These features have been termed 'Superposed LVF' and 'Small-scale Superposed LVF' by Levy et al. (2007), with the distinction being the scale of the feature. The Small-scale Superposed LVF is described as being present in only small-scale valleys of the order of a kilometer wide by five kilometers long and terminate in abrupt convex-up lobate fronts that are distinctive from and lie above main trunk bodies of LVF. Levy et al. (2007) attribute these flows...
Amazonian glacial events in Deuteronilus Mensae, Mars

Fig. 15. Linear ridges along the walls of alcoves cut within the flanks of the main plateau. We interpret these ridges to be lateral moraines that represent the former elevations of LVF. (Top image) Context view of region demonstrating the parallel nature of the ridges that are located at all elevations above the current locations of LVF deposits and extend for 100 s of meters in length. (Lower left image) Close-up view of the edge of the alcove. The ridges form discontinuous patterns and display convex forms in the downslope direction. (Lower right image) Highest resolution views of the ridges demonstrating their topographic form, which is highlighted by the occurrence of shadows to the north of the ridges (Sun from the southwest). Boulders form scree on the slopes extending up to the ridges. All images are subset of HiRISE image: PSP_006806_2215, north is to the top of the images.

to alcove microclimates that permitted the accumulation of small volumes of ice during periods of climatic conditions unfavorable to large scale regional glaciation. Within the Protonilus Mensae–Coloe Fossae region there are examples of superimposed lobes that exhibit terminal moraines that sit above the main trunk valley LVF (Dickson et al., 2008). The lack of modification and/or deflection within the superimposed moraines is highlighted by Dickson et al. (2008) as evidence that the lobe does not represent a reorganization of ice flow during the waning stages of glaciation, but rather was emplaced during a later renewed phase of glacial activity.

The occurrence of identical superimposed landforms thousands of kilometers apart suggests that additional features may exist
Fig. 16. Lobe of LVF emerging from an alcove that appears to be superimposed on, rather than merging with, the main branch of LDA onto which it flows (left panel). The entirety of the lobe is visible above the main body of the LVF, and there appears to be none of the disturbance within the main body such as is observable in Figs. 9 and 10. (b) The direction of flow of the lobe is indicated by the small arrows; the large arrows indicate the flow patterns of the main branch of LDA onto which the lobe sits (right panel). Other such features have been observed and documented in other regions of the dichotomy boundary (e.g. Levy et al., 2007; Dickson et al., 2008), and are interpreted to represent a second, later and less extensive phase of glacial emplacement. HRSC image 1589.

Fig. 17. The locations of detailed studies that have identified evidence for multiple episodes of LVF emplacement across the northern dichotomy boundary. The occurrence of such features over 2000 km apart suggests that more recent episodes of LVF activity were occurring across the northern dichotomy boundary. Map is a shaded relief of gridded MOLA topography data.
elsewhere across the dichotomy boundary (Fig. 17), and should be a focus of attention for future research. The distance between the locations in which these features have formed suggests that a more recent phase of glaciation has occurred across the northern dichotomy boundary since the emplacement of the main bodies of LVF/LDA around 100–500 million years ago. The small size (1–2 km wide) of the more recently emplaced LVF lobes argues that if the glacial model for LVF/LDA formation is correct, then the most recent glacial phases must have been characterized by climatic changes of a more limited magnitude and shorter duration.

8. Conclusions

We used new spacecraft data to carry out an in-depth investigation of lineated valley fill and lobate debris apron systems in a previously undocumented area of the dichotomy boundary. Our investigations provide persuasive evidence that debris-covered glaciation has played a significant role in the formation of these deposits. We reach the following conclusions:

1. Evidence has been documented for numerous, localized alcoves, enclaves and tributary valleys within the walls of plateaus and mesas which provide a source of small scale LVF flows and lobes; we interpret these flows to be the remnants of debris-covered glaciers that formed from the deposition of ice within the alcoves during previous preferential climatic regimes associated with higher planetary obliquities (Madeleine et al., 2007).

2. We found abundant evidence that LVF and LDA within the study region is comprised of the same material, show integrated flow patterns, and are of the same origin; this is supported by both landform types being supplied from individual lobes from within alcoves and the observations that LVF and LDA integrate seamlessly throughout the study area.

3. We present evidence to suggest that the LDA/LVF deposits within the study area have undergone a significant amount of modification since their emplacement. This has been in the form of both potential ice loss from sublimation related process to generate the pitted and butte texture of their surfaces (which has been described by Mangold, 2003; Levy et al., 2009) and through the formation of IU along the margins of the LVF/LDA with the surrounding valley flanks due to recent mass wasting processes.

4. We have mapped out large scale integrated systems of LVF and LDA, reminiscent of terrestrial glacial land systems; the nature of the integration is well illustrated by the expressions on the surface of LVF displaying compression between topographic obstacles and divergence around them.

5. We present evidence for former highstands of the LDA/LVF that suggest that the surface may have been more than 800 m higher during the full glacial phase than the thickness of the residual deposits today.

6. On the basis of superimposed impact craters, we derive a late Amazonian age for emplacement of the main body of LVF/LDA deposits. This may have coincided with a period of high obliquity, causing the loss of water ice at the polar caps and the redistribution of volatiles to lower latitudes (Carr, 1996; Carr et al., 2006a; Levy et al., 2007).

7. We outline evidence for multiple phases or cycles of LVF emplacement, possibly due to further perturbations of orbital parameters that were of a lesser extent than that responsible for the original LDA/LVF emplacement.

8. Modification of the fretted valleys of the dichotomy boundary has been substantial locally, as evidenced by the erosion of numerous alcoves, several-tens of kilometers in length into the flanks of the highlands and isolated mesas. However, we find no evidence that the Amazonian glacial epochs caused substantial retreat of the dichotomy boundary measured in the tens to hundreds of kilometers.

Our findings support the results of an analysis just to the east of the study region (Head et al., 2006b) and of studies carried out elsewhere along the dichotomy boundary (Head et al., 2006a; Levy et al., 2007; Dickson et al., 2008; Kress et al., 2008) that find further evidence for the past presence of debris-covered glaciers and extensive valley glacial land systems.

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