Late Amazonian glaciation at the dichotomy boundary on Mars: Evidence for glacial thickness maxima and multiple glacial phases

James L. Dickson
James W. Head — Department of Geological Sciences, Brown University, Providence, Rhode Island 02912, USA
David R. Marchant — Department of Earth Sciences, Boston University, Boston, Massachusetts 02215, USA

ABSTRACT

Lineated valley fill (LVF) in fretted valleys at the dichotomy boundary has been interpreted as glacial in origin. Unknown are (1) the original thickness of the glacier ice, (2) the amount of ice-surface lowering, through sublimation and retreat, to its presently observed level, and (3) whether there were multiple periods of glaciation. We address these questions through analysis of an LVF glacial system. The elevation difference between the upper limit of a previous highstand and the current surface of the LVF at the study site is ~920 m. We interpret this difference to be the minimum amount of ice-surface lowering of the glacier system. Consistent with a general lowering of the ice surface are multiple moraines and/or trimlines, and changes in LVF flow patterns, as the ice retreated and decreased in thickness. The superposition of several lobes onto the current surface of the LVF indicates that a phase of alpine glaciation followed the lowering of the valley glacial system. These data suggest that the Late Amazonian glaciation that produced LVF in this region involved significantly larger amounts of ice than previously thought, and that subsequent alpine glaciation followed.

Keywords: glaciers, glaciation, Mars, lineated valley fill, climate change.

INTRODUCTION

Recent study has revealed evidence for ice-related deposits in nonpolar regions of Mars, including tropical mountain glaciers (e.g., Head and Marchant, 2003), midlatitude ice-rich and glacier-like flows (e.g., Lucchitta, 1981; Squyres and Carr, 1986; Pierce and Crown, 2003), and latitude-dependent dust-ice mantles (e.g., Head et al., 2003). Deposition of large quantities of ice down to tropical latitudes in the past history of Mars is consistent with predictions of spin-axis and orbital variations during such periods (e.g., Laskar et al., 2004) and atmospheric general circulation models (e.g., Forget et al., 2006).

The northern lowlands of Mars are separated from the southern highlands by the crustal dichotomy boundary. The best-defined portion of the boundary occurs as a set of scarps, reentrants, and massifs where the boundary extends into northern midlatitudes (~25°–47° N), between 0° and 80° E (Fig. 1). A large portion of the boundary (northern part of Arabia Terra) is composed of fretted terrain and fretted channels and is the site of lineated valley fill (LVF) and lobate debris aprons (LDAs) (Squyres, 1978, 1979; Lucchitta, 1981). The LDA and LVF are characterized by lobate outlines and low slopes and have historically been interpreted to be related to flow of debris lubricated by groundwater or ice, with ice supplied by vapor diffusion and condensation in talus (e.g., Squyres, 1978; Lucchitta, 1984).

Recent studies have used high-resolution image and altimetry data, together with terrestrial glacial analogs, to show that LVF forms integrated patterns that represent flow beginning at multiple alcoves, and conver-gence, coalescence, and flow for hundreds of kilometers downvalley, ending in steep-fronted lobes in adjacent lowlands; these patterns are similar to valley glacial landsystems on Earth (e.g., Head et al., 2006a, 2006b). LDAs consist of multiple lobate flows, beginning in alcoves and extending into adjacent lowlands; these features are similar to remnants of terrestrial debris-covered glaciers (e.g., Head et al., 2005; Marchant and Head, 2007). LDAs often merge into LVF, often terminating in LDA-like lobes; this suggests an intimate relationship between the two and a common origin related to regional glaciation (e.g., Head et al., 2006a, 2006b). These recent interpretations of the LVF/LDA as representing integrated glacial landsystems (e.g., Benn et al., 2003) imply that (1) the muted patterns that we see are relict patterns and represent a fraction of the original system; (2) the surface has experienced modification since the time of maximum glaciation (retreat, sublimation, periglacial, eolian, mass wasting, etc.); (3) exposed ice no longer remains on the surface, but in places may remain protected under thick layers of sublimation till; (4) convolved in the observed patterns is the record of glacial retreat and downwasting (trimlines, flow reversals, moraines, highstands, etc.); and (5) superposed on these patterns is a record of (a) subsequent crater impact and erosion, and (b) recurrent glacial phases. Major outstanding questions include the following: (1) What was the original areal and vertical extent of glacier ice? (2) What are the original volumes of ice transported to, and deposited in, these areas? (3) Is there evidence for multiple phases of glaciation? We report here on an example from Protonilus Mensae, near Coloe Fossae, in which we observe evidence of former highstand elevations of LVF ~920 m above the present level, and distinct lobate alpine glacial deposits clearly superposed on, and crosscutting, LVF.

LDA/LVF IN THE PROTONILUS MENSAE–COLOE FOSSAE REGION

A steep scarp at the dichotomy boundary separates the southern plateau from the northern lowlands, ~3 km below (Fig. 1). The boundary region is characterized by breakup of the plateau (C in Fig. 1B) into isolated massifs and mesas (e.g., A and B in Fig. 1B). On the northeastern margin of Arabia Terra along the dichotomy, a series of grabens (Coloe Fossae; D in Fig. 1B) strike NW-SE and dissect the plateau. The massifs are surrounded by LDA (Figs. 1A and 1B), the scarp is characterized by linear LDA, the graben by LVF, and LDA and LVF are interrelated in regionally coherent patterns (Figs. 1B and 2). The fretted terrain formed prior to the middle Hesperian, and the associated LVF and LDAs represent Amazonian-aged modification of the fretted topography. The low-sloped LVF occupies the graben and intermassif valleys and occurs at elevations as high as 1500–1900 m above the edge of the marginal or terminal lobes extending into the lowlands (Fig. 1B). The trends of the surface texture of LDA/LVF, and the flow patterns they reveal, are mapped in Figures 1B and 2B. On the basis of these patterns, LDAs are interpreted to have formed in alcoves along the scarp and massif margins, flowed downslope, and converged with other LDAs, combining to form the integrated patterns of LVF. The flow patterns for LVF/LDA observed today (Figs. 1B and 2B) record a snapshot of the last phases of flow, and so record only minimum ice configurations. More extensive glaciation could have occurred. If so, the ice would have mantled the elevated plateaus, shutting off supraglacial rockfall to the system. Without debris, and with minimal basal entrainment possible given frozen-bed thermal conditions, geomorphic evidence for glaciers' overriding of the plateaus and neighboring uplands would be sparse and not be discernable at the resolution examined here. The regional patterns (Figs. 1B and 2B) suggest that following maximum advance, and during the last phases of ice flow, late-stage accumulation zones were in Coloe Fossae, in fretted valleys, in alcoves along the
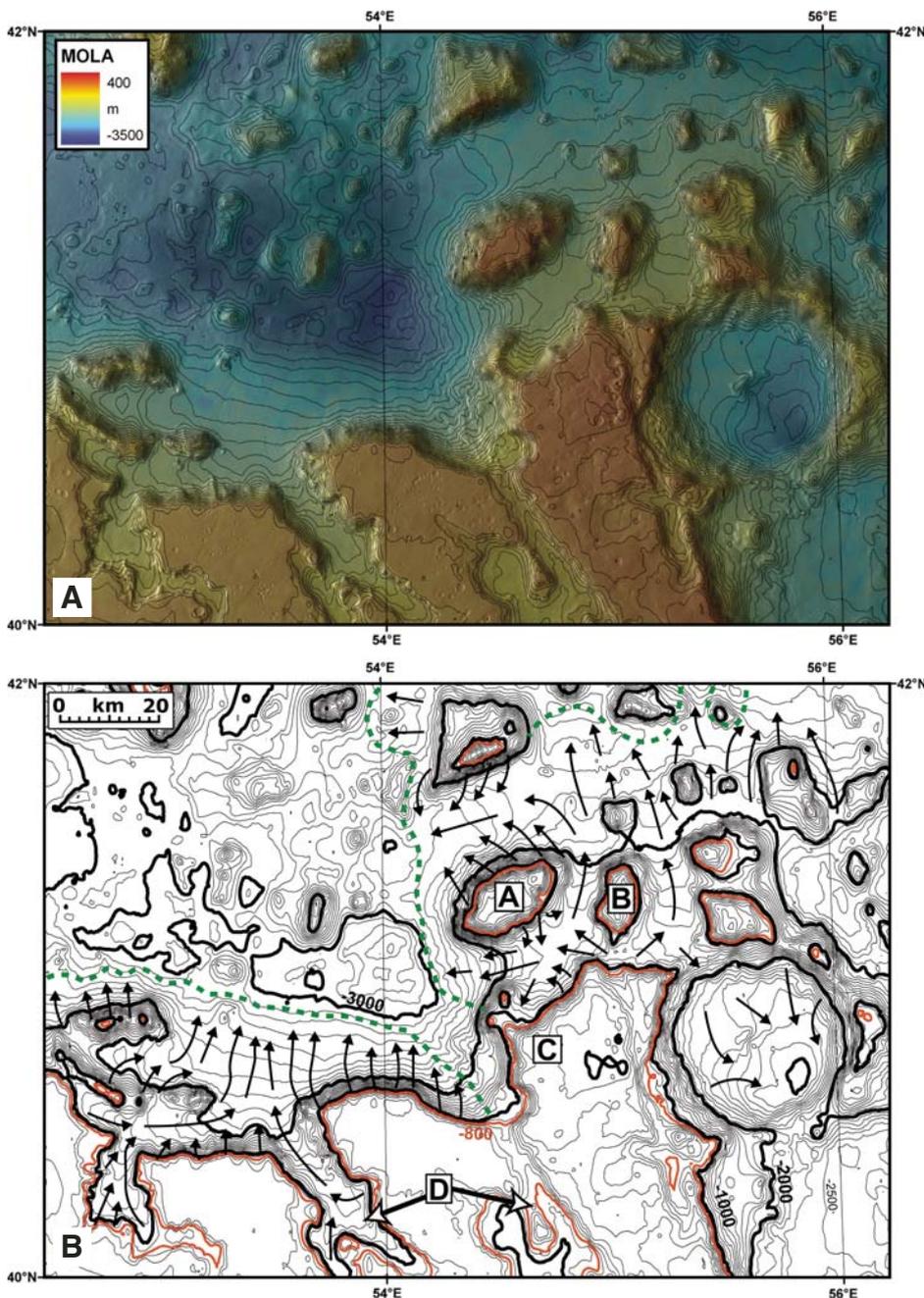
Figure 1. Protonilus Mensae–Coloe Fossae region. A: Thermal Emission Imaging System (THEMIS) image mosaic on Mars Orbiter Laser Altimeter altimetry. B: Topographic map; 100 m contours. Green dashed lines are borders of lobate debris apron (LDA)/lineated valley fill (LVF) deposits; arrows represent flow patterns mapped in LDA/LVF. Orange line is –800 m contour representing the uppermost position of the loop-shaped lobe (arrow just NW of letter C) in Figure 2. Letters refer to plateaus described in text.

bounding scarp, and in alcoves surrounding the massifs, with flow extending away from these regions into local lows (see arrows in Figs. 1B and 2B).

EVIDENCE FOR THE FORMER THICKNESS OF LVF

Reconstructions of flow directions revealed an anomalous area in which a 5-km-wide, loop-like lobe extends from the LVF on the valley floor up into an elevated box canyon (Dickson et al., 2006) (Figs. 2A and 2C). This is opposite the situation usually encountered, in which flow extends from high-elevation alcoves out onto low-lying areas in lobe-like configurations (Fig. 2D). On the basis of the map view of the lobe morphology, the lobe appears to have been an extension of flow from the central part of the valley into this alcove, compressing and undergoing folding as it abutted the wall (Figs. 2B

and 2C). Mars Orbiter Laser Altimeter (MOLA) profiles show that the distal edge of the LVF lobe surface at the highest point in the alcove is at –800 m, ~920 m above LVF in the adjacent valley (Fig. 3; Fig. DR1 in the GSA Data Repository[1]), which itself is ~1300 m above the surrounding plains to the west (Fig. 1B).

The implication of this geometry is that the isolated lobe represents a remnant of the former lateral extent of LVF that would provide an estimate of the vertical downwasting during retreat. A test of this interpretation is to extrapolate the elevation of the inferred limit elsewhere in the area and look for additional evidence of an upper limit. To do so, we extrapolated the –800 m contour line (orange contour in Figs. 1B and 2B) across the mapped area and found that it corresponds to linear ridges found at the margins of the main plateau and outlying massifs. For example, the southern and western margins of massif A (Figs. 2A and 2B) contain a series of roughly horizontal ridges (Fig. DR2) that we interpret as marginal moraines. The ridges occur within a narrow band restricted to a few hundred meters above and below the –800 m contour.

PREDICTED BEHAVIOR DURING GLACIAL RECESSION

On the basis of these observations, our hypothesis is that glaciation in this area was more extensive during its peak development than is currently recorded in the LDA/LVF textures alone. The configuration of the LDA/LVF (Figs. 1, 2A, and 2B) represents a snapshot of the terminal phase of this particular glaciation, i.e., at a point where backwasting and downwasting dominated.

What is the predicted behavior of ice flow between peak development and the terminal snapshot? On Earth, continental-scale glaciation during the last glacial maximum in the High Arctic gave way to plateau icefields and ultimately to valley glacial landsystems (Benn et al., 2003).

In the Coloe Fossae region, we predict a similar transition, with the valleys initially filled with flowing glacial ice (at or above the –800 m contour). During this phase, lobes of glacial ice extended from the accumulation zones into the surrounding valleys (see diverging arrows in Figs. 1B and 2B) and then out into the surrounding lowlands; one of these lobes flowed into the elevated box canyon, forming the isolated lobe (Fig. 2; gold arrows in Fig. DR3). As this phase of glaciation drew to a close, accumulation decreased and ice retreated from the lowlands back toward the dichotomy boundary. Even though flow continued, the glacier surface lowered, exposing
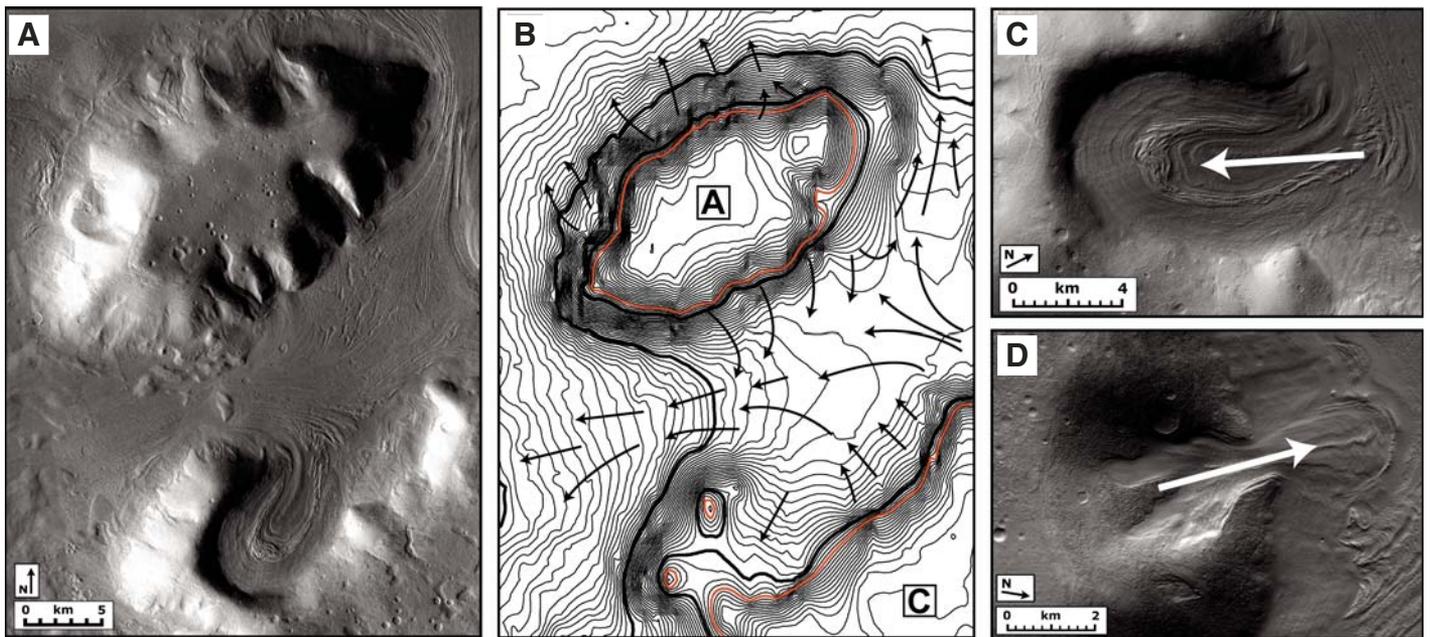
Figure 2. Plateau and adjacent isolated massifs (east-central part of Fig. 1). Lobate debris apron (LDA)/ lineated valley fill (LVF) form distinctive patterns in tributaries and on valley floor. A: Mars Reconnaissance Orbiter Context Camera image PO1_001570_2213_XI_41N305W (same in all figures). B: Topographic map; 100 m contours. Arrows represent flow patterns mapped in LDA/LVF. Orange line is –800 m contour (uppermost position of the loop-shaped lobe). C: Loop-shaped lobe entering into the box canyon, with ice sourced from the main valley (see Fig. DR3 for detail). White arrow indicates interpreted flow direction. D: Tributary debris-covered glacier emerging from the northern slope of massif A and joining the main valley. White arrow indicates interpreted flow direction. Note patterns emerging from the upper parts of the valley, coalescing downslope, and producing a lobate flow feature as it emerges from the tributary onto the valley floor. Note also the differences between the patterns associated with flow into the box canyon (C) and out of the tributary (D).

more mountainous topography. The exposed topography altered glacial flow patterns, and with continued lowering, local topography (alcoves and small valleys) played an increasing role in influencing flow patterns. Furthermore, newly exposed bedrock provided a source region for supraglacial debris. As debris falls on ice it contributes to a transition from ice-dominated glacier surfaces to debris-covered glaciers. We suggest that as the regional glacial landsystem evolved and alcove-focused debris-covered glaciers began to dominate, new patterns of glacial flow evolved, including single to multiple sources, and in some cases reversal of flow direction.

In the case of the loop-like lobe in the box canyon, such late-stage transitions are evident. A reconstruction of the original configuration near peak glaciation (Fig. DR3, broad arrows) shows the lobe extending into the valley, compressing to form the ridges, and stagnating there, while the major part of the flow continued down the main trunk valley just to the north. As the glacial system began to recede, the level of ice in the main valleys lowered and left the upper part of the loop-like lobe at the –800 m elevation level (Fig. 3). This is likely to have encouraged reverse flow, for which there is evidence in the flow patterns of the loop-like lobe (Fig. DR3, white lobes and arrows). As the glacial surface continued to lower, topography played an increasing role in modulating local sources of ice, and coalescing debris-covered glaciers began to dominate. This
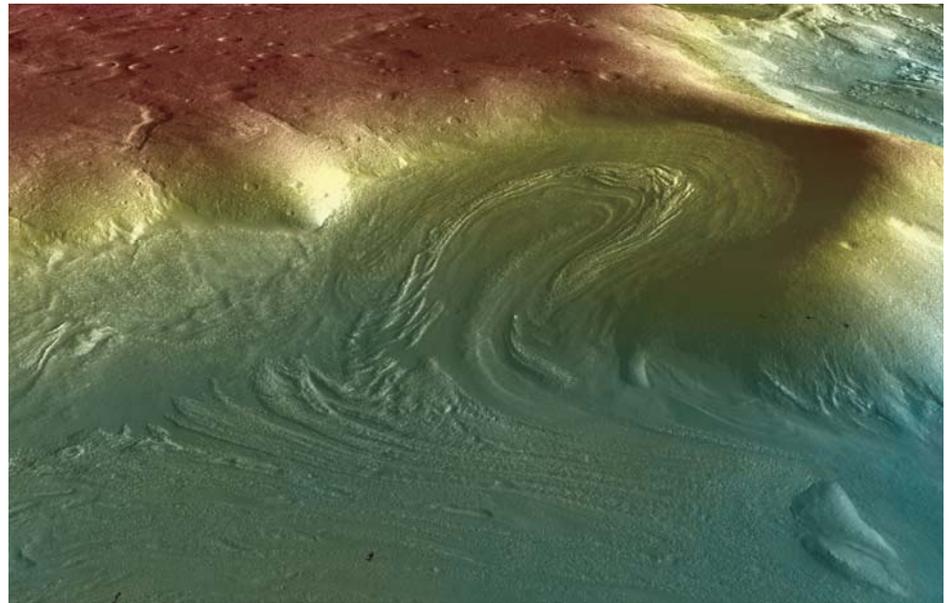
Figure 3. Perspective view from the valley into the box canyon (along a profile shown in Fig. DR1) showing flow features that now trend upslope (see Fig. DR3 for detailed patterns). Mars Reconnaissance Orbiter Context Camera image draped on High Resolution Stereo Camera topography from orbit h2908. No vertical exaggeration.

is seen at the eastern part of the loop-like lobe, where a series of late-stage lobes descend from the valley walls and converge with the main valley glacial flow, deforming the loop-like lobe in the process (Fig. DR3). Lobes become increasingly compressed into chevrons until they are integrated into the LVF. This present configuration is a snapshot of the final phase of glacial flow, when the glacier geometry no longer provided the forces for glacial movement.
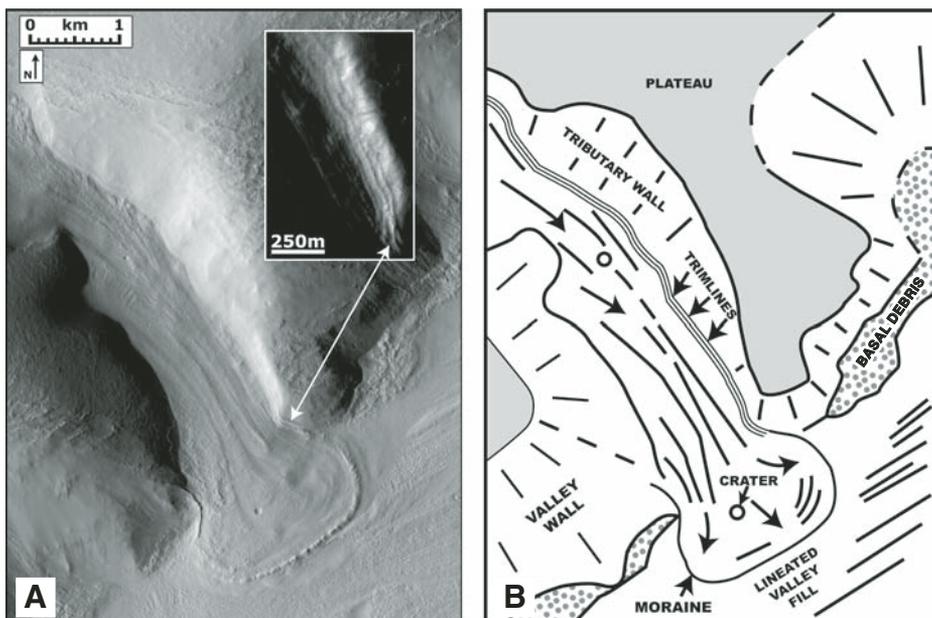
Figure 4. Debris-covered, glacier-like lobe emerging from a tributary on the southern wall of massif A (Fig. 1A; also see image in Fig. 2A). A: Mars Reconnaissance Orbiter Context Camera image. B: Sketch map showing main features and relationships. Note that the lobe extends out onto the floor, crosscutting linear trends in the lineated valley fill (LVF), and appears topographically superposed on the LVF. The inset shows evidence for lateral moraines along the tributary wall, suggesting the progressive loss of ice down to the present topographic level.

EVIDENCE FOR POST-LDA/LVF GLACIAL ACTIVITY

Evidence for renewed glacial conditions subsequent to LDA/LVF formation is seen in features interpreted to be crosscutting and superposed lobate debris-covered glaciers and glacial deposits (Fig. 4). In several cases, lobate flow-like features emanating from tributary alcoves extend downslope and emerge onto the valley floor. Clear relative age relationships are seen (Fig. 4): The lobes are superposed on the linear trends in the LVF, similar to patterns observed elsewhere along the dichotomy boundary (Levy et al., 2007). In Figure 4A (inset), evidence for subsequent downwasting of a tributary lobe is seen in the position of marginal moraines and/or trimlines along the valley wall. Although it is possible that superposition could represent ice-flow reorganization during the final phase of glaciation, we favor a model that calls for renewed glaciation because superposed moraines show no deflection and/or modification, suggesting that flow associated with the major glaciation had ceased. The elapsed time between the major phase of glaciation and the renewed phase of alpine glaciation is unknown.

CONCLUSIONS

A distinctive lobe of LVF in a box canyon is interpreted to represent a former glacial highstand, providing evidence that the current surface of adjacent LVF, ~1500 m above the plains, was at least 920 m higher during peak glaciation.

The present flow patterns provide insight into the latest phases of an originally more extensive glacial landsystem; the peak thickness of the glacial system was possibly as much as 2.5 km. Evidence for a renewed but less extensive phase of glaciation is seen in superposed lobes interpreted to be debris-covered glacier remnants.

REFERENCES CITED

Benn, D.I., Kirkbride, M.P., Owen, L.A., and Brazier, V., 2003, Glaciated valley landsystems, *in* Evans, D., ed., Glacial landsystems: London, Arnold, p. 372–406.

Dickson, J.L., Head, J.W., and Marchant, D.R., 2006, Modification of graben along the dichotomy boundary in eastern Arabia Terra (Coloe Fossae; 53–59°E, 37–41°N): Nature and evolution of lobate debris aprons and their relationships to lineated valley fill and glacial systems: Proceedings of the 37th Lunar and Planetary Science Conference, p. 1317.

Forget, F., Haberle, R.M., Montmessin, F., Levrard, B., and Head, J.W., 2006, Formation of glaciers on mars by atmospheric precipitation at high obliquity: Science, v. 311, p. 368–371, doi: 10.1126/science.1120335.

Head, J.W., and Marchant, D.R., 2003, Cold-based mountain glaciers on Mars: Western Arsia Mons: Geology, v. 31, p. 641, doi: 10.1130/0091-7613(2003)031<0641:CMGOMW>2.0.CO;2.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., and Marchant, D.R., 2003, Recent ice ages on Mars: Nature, v. 426, p. 797–802, doi: 10.1038/nature02114.

Head, J.W., Neukum, G., Jaumann, R., Hiesinger, H., Hauber, E., Carr, M., Masson, P., Foing, B., Hoffmann, H., Kreslavsky, M., Werner, S., Milkovich, S., van Gasselt, S., and the HRSC Co-Investigator Team, 2005, Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars: Nature, v. 434, p. 346–351, doi: 10.1038/nature03359.

Head, J.W., Marchant, D.R., Agnew, M.C., Fassett, C.I., and Kreslavsky, M.A., 2006a, Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change: Earth and Planetary Science Letters, v. 241, p. 663–671, doi: 10.1016/j.epsl.2005.11.016.

Head, J.W., Nahm, A.L., Marchant, D.R., and Neukum, G., 2006b, Modification of the dichotomy boundary on Mars by Amazonian mid-latitude regional glaciation: Geophysical Research Letters, v. 33, L08S03, doi: 10.1029/2005GL024360.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., and Robutel, P., 2004, Long-term evolution and chaotic diffusion of the insolation quantities of Mars: Icarus, v. 170, p. 343–364, doi: 10.1016/j.icarus.2004.04.005.

Levy, J.S., Head, J.W., and Marchant, D.R., 2007, Lineated valley fill and lobate debris apron stratigraphy in Nilosyrtis Mensae, Mars: Evidence for phases of glacial modification of the dichotomy boundary: Journal of Geophysical Research, v. 112, E08004, doi: 10.1029/2006JE002852.

Lucchitta, B.K., 1981, Mars and Earth: Comparison of cold-climate features: Icarus, v. 45, p. 264–303.

Lucchitta, B.K., 1984, Ice and debris in the fretted terrain, Mars: Proceedings of the Lunar and Planetary Science Conference, v. 14, no. 2, p. B409–B418.

Marchant, D.R., and Head, J.W., 2007, Antarctic dry valleys: Microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars: Icarus, v. 192, p. 187–222, doi: 10.1016/j.icarus.2007.06.018.

Pierce, T.L., and Crown, D.A., 2003, Morphologic and topographic analyses of debris aprons in the eastern Hellas region, Mars: Icarus, v. 163, p. 46–65, doi: 10.1016/S0019-1035(03)00046-0.

Squyres, S.W., 1978, Martian fretted terrain: Flow of erosional debris: Icarus, v. 34, p. 600–613, doi: 10.1016/0019-1035(78)90048-9.

Squyres, S.W., 1979, The distribution of lobate debris aprons and similar flows on Mars: Journal of Geophysical Research, v. 84, p. 8087–8096.

Squyres, S.W., and Carr, M.H., 1986, Geomorphic evidence for the distribution of ground ice on mars: Science, v. 231, p. 249–252.