

**NORTHERN MID-LATITUDE GLACIATION IN THE AMAZONIAN PERIOD OF MARS: GLOBAL-SCALE DEBRIS-COVERED GLACIER AND VALLEY GLACIER DEPOSITS IN THE 30°-50° N LATITUDE BAND.** J. W. Head<sup>1</sup> and D. R. Marchant<sup>2</sup>, <sup>1</sup>Dept. Geol. Sci., Brown Univ., Providence, RI 02912 USA (james\_head@brown.edu), <sup>2</sup>Dept. Earth Sci., Boston Univ., Boston, MA 02215 USA (marchant@bu.edu).

**Introduction:** Terrestrial cold-based glacial analogs [1,2] have recently been applied to the analysis of fan-shaped deposits on the NW flanks of the Tharsis Montes and Olympus Mons, interpreting them to represent extensive tropical mountain glaciers formed by enhanced snow and ice deposition during periods of high obliquity in the Amazonian [3-8]. Additional Earth glacial analogs have been used to develop criteria for the recognition of glacial deposits in various topographic and environmental settings on Mars [9]. These criteria have recently been applied to the assessment of the fretted terrain, one of the hallmark morphologies of the high-lowland boundary region in the northern mid-latitude Deuteronilus-Protonilus Mensae area (30°-50° N and 10° -75° E). The fretted terrain [e.g., 10] consists of 1) lobate debris aprons (LDA) that surround many of the massifs and valley walls, and 2) lineated valley fill (LVF) that occurs on the floors of many of the valleys. We addressed the question of whether the accumulation of snow and ice, and resulting glacial activity, could account for some of the observed characteristics of the fretted terrain. In one area (Fig. 1; 1)(~37.5° N, 24.2° E) [11] evidence was presented that lineated valley fill formed in multiple accumulation zones in breached craters, alcoves, and tributary valleys and flowed laterally down-valley forming a major trunk system that was characterized by compression of ridges at constrictions, tight folds at converging branches, and a lobate, convex-upward terminus. In a second area (Fig. 1; 2)(~40.5° N, 34.5° E) [12] a single integrated system was documented covering ~30,000 km<sup>2</sup> and consisting of multiple, theater-headed, alcove-like accumulation areas, converging patterns of down-slope flow into several major valley systems, and broad piedmont-like lobes where the LVF extended out into the adjacent lowlands. The features and deposits in these two areas are interpreted to represent intermontaine valley glacial systems dating from earlier in the Amazonian.

**Synthesis of criteria for recognition:** Using the range of terrestrial analogs and the subset most likely to apply to the recent cold desert environment of Mars [e.g., 1,2,9], the following criteria have been developed to assist in the identification of debris-covered glacial-related terrains on Mars; the interpretation of each is listed in parentheses: 1) alcoves, theater-shaped indentations in valley and massif walls (local snow and ice accumulation zones and sources of rock debris cover), 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 where abutting 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 intermontaine glacial systems), 9) se-

quential 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 in valleys and that open in a down-slope direction (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 (intermontaine glacial systems), 14) rounded valley wall corners where flow converges downstream, and narrow arete-like plateau remnants between LVF valleys (both interpreted to be due to valley glacial streamlining).

Taken together, the occurrence of these features is interpreted to represent the former presence of debris-covered glaciers and valley glacial systems in the Deuteronilus-Protonilus region [11,12]. Snow and ice accumulating in alcoves, together with rock debris shed from adjacent steep walls, created debris-covered glaciers that flowed down-slope, merging with other ice lobes to form ever-larger LVF glacial systems.

**Application to other parts of the Deuteronilus-Protonilus region:** These criteria have been applied to detailed analyses of eight additional areas in this region (Fig. 1; 3-10) [13-20] and reconnaissance assessments of many other areas along the dichotomy boundary have been undertaken. Among the most important findings are: 1) Lobate debris aprons (LDA) can be subdivided into linear (along valley walls and degraded crater walls; Figs. 2a, 3b) and circumferential (around isolated massifs; Fig. 2b); 2) LDAs commonly form from numerous parallel individual flow lobes emanating from alcove-like indentations in massif and valley walls; Fig 2b; 3) in some cases LVF glacial systems clearly merge with linear LDAs (Fig. 3a); 4) in some cases linear LDAs derived from opposite valley walls merge and flow down valley (Fig 4); 5) in massif clusters, circumferential LDAs often meet those from adjacent massifs, merge, and then flow downslope, forming piedmont-like lobate terminations in the adjacent lowlands (Figs. 5, 7); 6) the location and distribution of these features (Fig. 1) strongly suggest regional intermontaine valley glacial systems whose locations are dictated by topographic configurations (dichotomy boundary scarps, massifs, valleys and craters) conducive to accumulation and preservation of snow and ice and the formation of rock debris cover; 7) topographic and morphologic relationships suggest that some valley glacial systems may be partly fed from local plateau icefields (Fig. 6). In summary, the Deuteronilus-Protonilus region (Fig. 1) was an area of active and very widespread glaciation during parts of the Amazonian.

**Assessment of other regions in the 30°-50° N latitude range:** The presence of valley glaciers could be due to local environmental conditions in which the accumulation of snow and ice was favored [e.g., 21]. The widespread distribution of these glacial systems in the Deuteronilus-Protonilus highland region (Fig. 1), however, suggests that conditions were much more regional, extending across a significant latitude band. To

address the question of whether climatic conditions conducive to glacial activity extended beyond the Deuteronilus-Protonilus region, we undertook a systematic analysis of the remaining longitudes at these latitudes and found abundant evidence of local and regional Amazonian glacial deposits in the following areas (Fig. 1): **1) Elysium Rise: Hecates Tholus (Fig. 1; 11):** A 45 km wide depression at the base of Hecates Tholus is host to a series of debris covered glacial deposits [22]. **2) Phlegra Montes (Fig. 1; 12):** Debris-covered glacial deposits are located along the scarp of the montes as well as surrounding individual massifs there (e.g., 30°-50°N, 160°-167° E). **3) Arcadia Planitia (Fig. 1; 13):** Degraded mountains in central Arcadia contain debris-covered glacial deposits (e.g., 35°-40° N, 185°-190° E). **4) Acheron Fossae (Fig. 1; 14):** LVF and LDA of glacial origin are common in association with the graben and massifs [e.g., 23] (Fig. 7). **5) Tempe Terra Region (Fig. 1; 15):** LVF and LDA of glacial origin occur in numerous places in the graben and mountains (e.g., 45°-52° N, 280°-300° E).

**Atmospheric General Circulation Models: Conditions for Northern Mid-Latitude Glaciation:** Recent GCM analyses show that the major accumulations of water ice in the equatorial regions (to form the Late Amazonian tropical mountain glacier deposits [1-7]) most likely involved precipitation and deposition during periods of high obliquity (~45°). We examined the fate of these huge tropical mountain glaciers following a return to lower obliquity (~35°) [24-25] and found that a meteorological consequence of this large equatorial reservoir was the formation of a thick cloud belt in the northern mid-latitudes of Mars. The thermodynamic state of the atmosphere results in increased meridional circulation, a strong eastward jet during northern winter, and associated stationary planetary waves. If the atmosphere is relatively dusty, a condition expected in this configuration, then this new water cycle favors condensation and precipitation and preservation of water ice in the areas described above to thicknesses up to ~1000 m during a ~50 ky high obliquity cycle.

**Testing Interpretations with Glacial Flow Models:** We use guidelines from the GCMs [24-25] to model the snow and ice accumulation and flow behavior in this latitude region and assess the characteristics and evolution of accumulating ice in terms of flow patterns [26] in a manner similar to our analysis of the tropical mountain glaciers [27]. Accumulation in alcoves produces local down-slope flow, in time leading to convergence and coherent down-valley flow, and the formation of a well-developed valley glacier system extending to the mouths of the major valleys. The glaciers eventually extend out of the valleys and into the adjacent northern lowlands, in a configuration comparable to observations of the deposits [e.g., 12]. Expansion of the model clearly shows reproduction of local flow patterns [26, Figs. 5-7] observed in THEMIS images [e.g. 12]. These analyses provide strong support for the interpretations and help to assess the time scales and velocities involved in the valley glaci-

ation processes.

**Summary and conclusions:** 1) An array of terrestrial analogs for glacial processes that are applicable to the range of conditions on Mars have been developed [1-3,9,28]; 2) These have been used to test for the presence of deposits and sites of former valley glaciation and debris-covered glaciers (cold-based ice) in two specific areas of Mars [11,12]; 3) From these analyses, general criteria for the recognition of debris-covered glacial deposits have been outlined [9]; 4) Application of these criteria to the northern mid-latitudes reveals the presence of widespread cold-based glaciation in valleys and mountains and along scarps, in the 30°-50° N latitude band [13-20]; 5) The global-scale latitudinal distribution of these deposits (Fig. 1) suggests an extensive period in the Amazonian when ice was stable in this latitude band [29]; 6) A plausible explanation for this configuration is the formation of an extended period of spin-axis obliquity at ~35°, following the formation of tropical mountain glaciers at ~45° [see 8, 30-32]. Under these conditions, the northern mid-latitude band becomes the locus of deposition of ice mobilized from equatorial latitudes with sufficient accumulation to produce glaciers [24-25]; 7) Glacial flow models predict the general configuration and morphology of the observed deposits interpreted to be integrated glacial valley landsystems [26-27], adding confidence to this interpretation.

**References:** [1] D. Marchant and J. Head, *LPSC 34*, 1361, 2003; [2] D. Marchant and J. Head, *LPSC 35*, 1405, 2004; [3] J. Head and D. Marchant, *Geology*, 31, 641, 2003; [4] D. Shean et al., *JGR*, doi:10.1029/2004 JE002360, 2005; D. Shean et al., *JGR*, doi: 2006JE002761, 2007; [5] S. Milkovich et al., *Icarus*, 181, 388-407, doi: 10.1016/j.icarus.2005.12.006, 2006; [6] G. Neukum et al., *Nature*, 432, 356, 2004; [7] J. Head et al., *Nature*, 434, 336, 2005; [8] F. Forget et al., *Science*, 311, 368, 2006; [9] D. Marchant and J. Head, *LPSC 37*, 2006; [10] S. Squyres, *Icarus*, 34, 600, 1978. [11] J. Head et al., *EPSL*, 241, 663, 2005; [12] J. Head et al., *GRL*, 33, doi: 10.1029/2005GL024360, 2006; [13] A. Kress et al., *LPSC 37*, 1323, 2006; [14] J. Head et al., *LPSC 37*, 1126, 2006; [15] G. Morgan et al., *LPSC 37*, 2008, 2006; [16] A. Nahm et al., *LPSC 37*, 1186, 2006; [17] D. Marchant et al., *LPSC 37*, 1425, 2006; [18] J. Dickson et al., *LPSC 37*, 1317, 2006; [19] J. Dickson et al., *LPSC 37*, 1321, 2006; [20] J. Levy et al., *LPSC 37*, 1245, 2006; [21] M. Hecht, *Icarus*, 156, 373, 2002; [22] E. Hauber et al., *Nature*, 434, 356, 2005; [23] J. Dickson et al., *LPSC 37*, 2006; [24] J.-B. Madeleine et al., *LPSC 38*, 1778, 2007; [25] J.-B. Madeleine et al., *Mars 7*, this volume, 2007; [26] J. Fastook et al., *Mars 7*, this volume, 2007; [27] J. Fastook et al., *LPSC 38*, 1119, 2007; [28] D. Marchant and J. Head, *Icarus*, in revision, 2007; [29] J. Head and D. Marchant, *LPSC 37*, 1127, 2007; [30] F. Forget et al., *JGR*, 104, 24155, 1999; [31] M. Mishna et al., *JGR*, doi:10.1029/2003JE002051, 2003; [32] R. Haberle et al., *Icarus*, 161, 66, 2003.

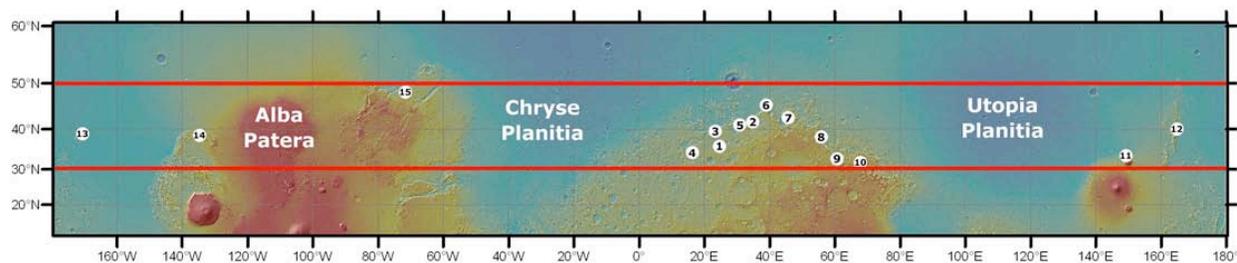


Fig. 1. Locations of areas showing evidence of glaci- ation discussed in this study. Red lines show 30°-50° N latitude band in which they occur.

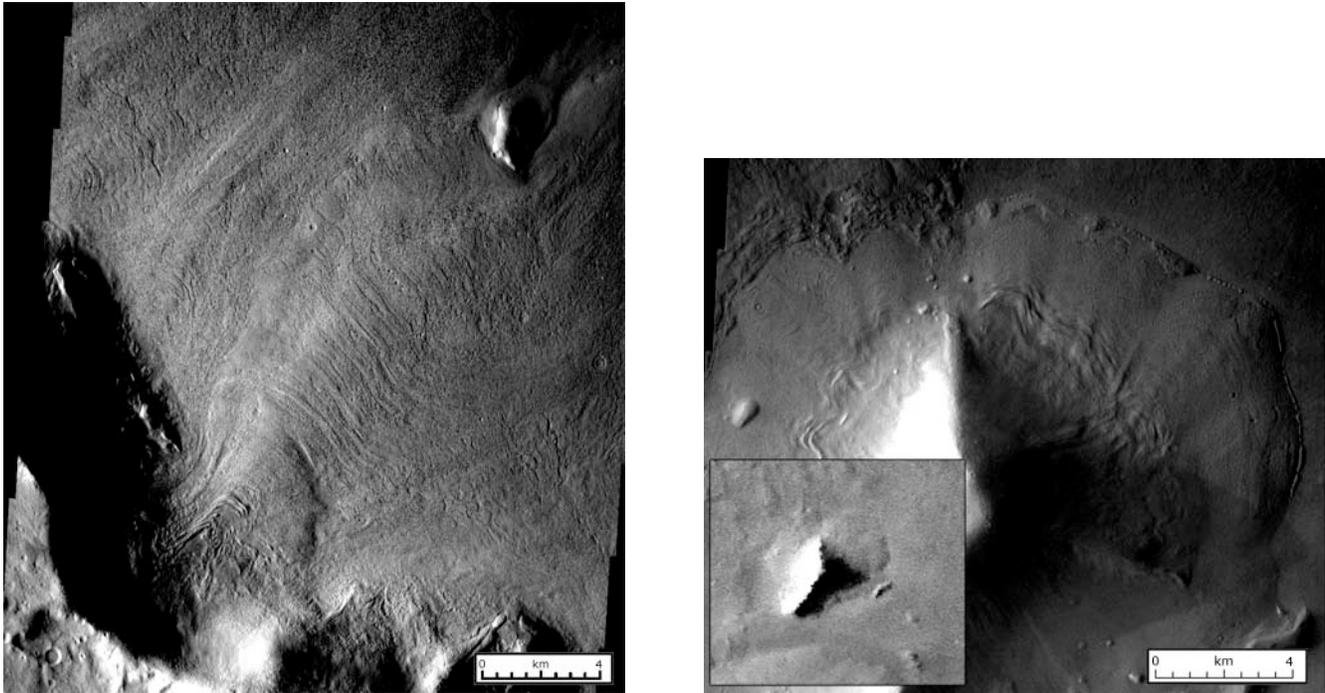


Fig. 2. Lobate and linear LDAs [14]: a) Linear LDA along a crater wall. Note alcoves, lobes, obstacle divergence. THEMIS V10834007. b) Massif with circumferential LDA. THEMIS V13879005, with Viking inset for comparison.

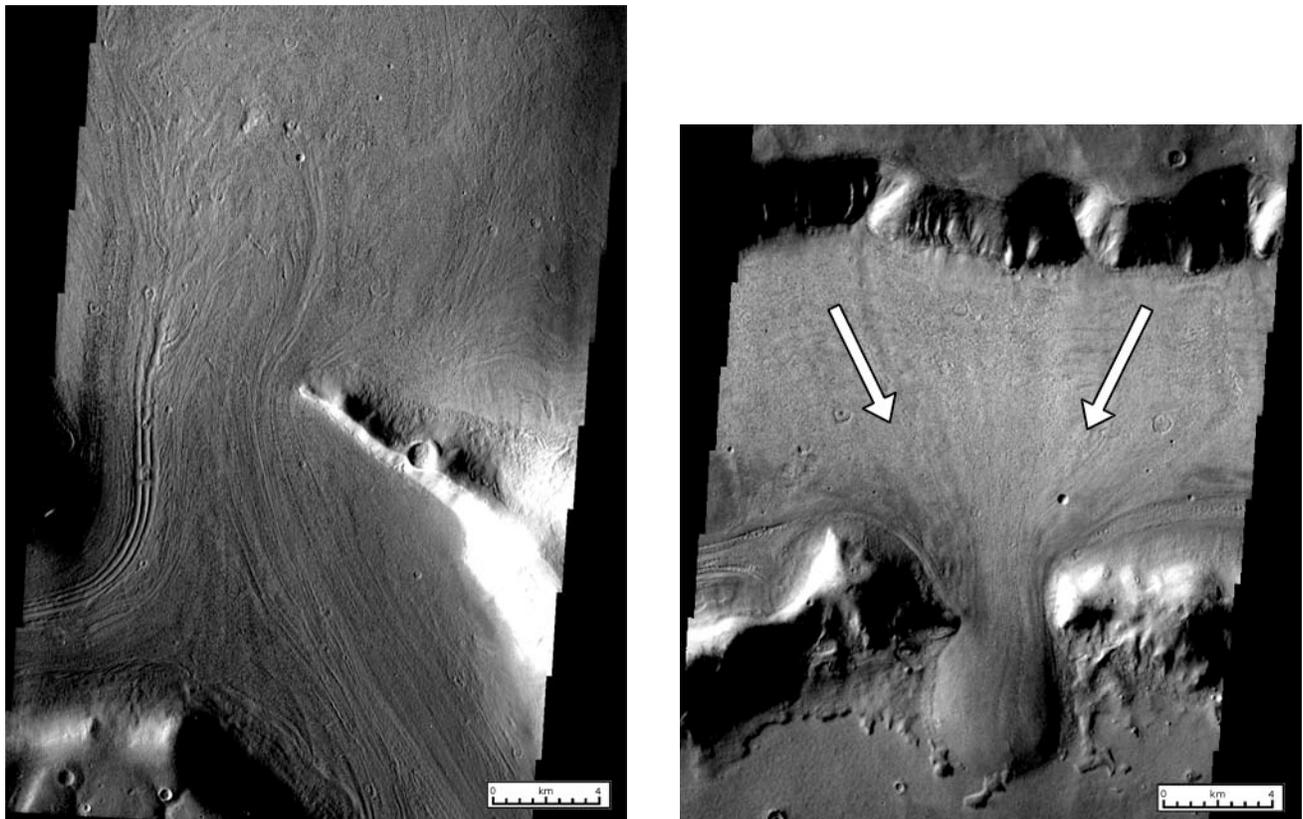


Fig. 3. Folds and lobes [14]: a) Large fold where LVF converges and becomes LDA. THEMIS V11433004. b) Linear LDA blocked by parallel ridges merges to form LVF and piedmont lobe in gap. THEMIS V12057009.



Fig. 4. LDAs meeting and distorted down-gradient [13]. THEMIS V10572015.

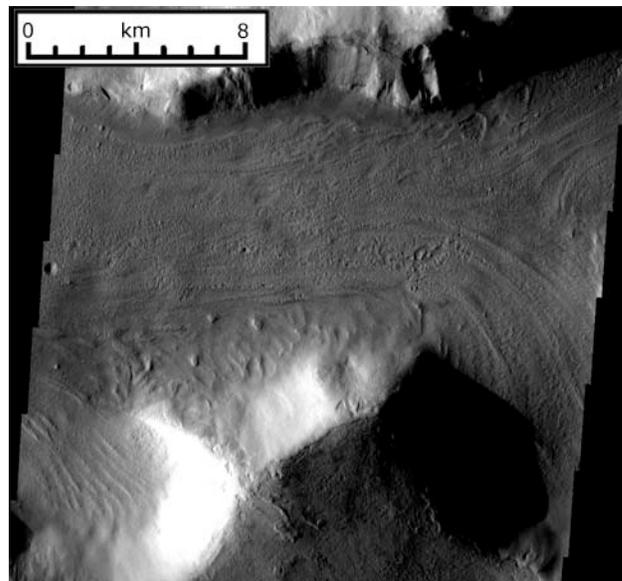


Fig. 5. LDAs converging into LDF [16]. THEMIS V13916010.

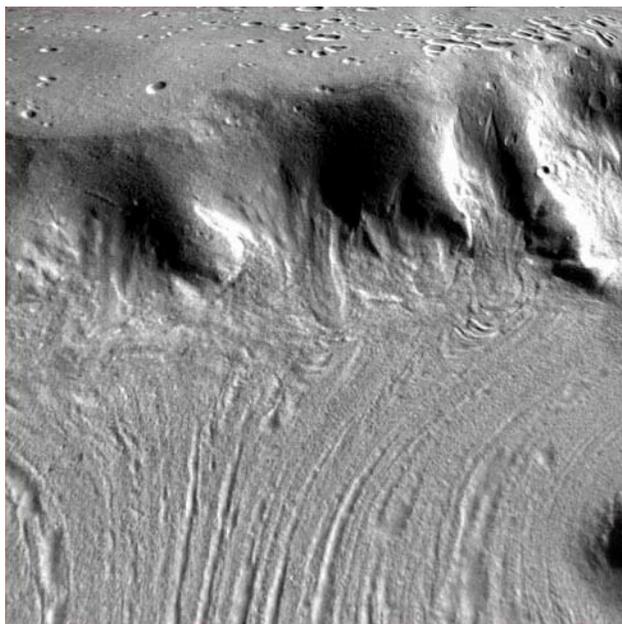


Fig. 6. LDAs at the edge of the dichotomy boundary converging down-slope to form LVF; note that the LDAs appear to emerge from the top of the plateau, suggesting the present of a plateau icefield feeding the valley glacial landsystem. THEMIS V03044003 draped on MOLA; VE = 5x.

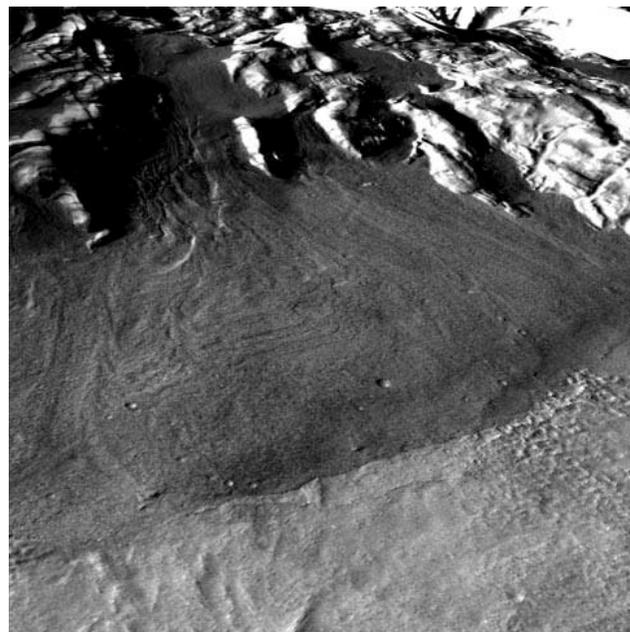


Fig. 7. Perspective view of piedmont-like LDA emerging from graben in Acheron Fossae [19]. THEMIS V09791029 and V01852010 draped on MOLA; VE = 2x