Periglacial Landscape Evolution at Lower Mid-Latitudes on Mars: The Thaumasia Highlands

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Abstract

We report on the detection of periglacial landforms at high mid-latitudes in the Thaumasia Highland (Mars) that are characterized by lobate to tongue-shaped flow and creep morphologies and which have a close resemblance to terrestrial landforms found in mountainous permafrost regions. It appears that pristine ice-related landforms are best described by small-scale protalus lobes, with few to no distinct impact craters at both HRSC and MOC NA scale. Exposure to solar insulation seems to control the distribution of rock glacier-like landforms, with a preferred occurrence on south-facing slopes. Older, less pristine lineated crater fills, which are commonly considered to represent landforms related to the viscous deformation of ice and debris, show, however, a less systematic distribution of flow directions. Both relatively young landforms are likely related to climatic variations on Mars orbital variations in its recent past and form the youngest witnesses of high obliquity.

Keywords: climate change; Mars; mid-latitudes; periglacial landforms; protalus lobes.

Introduction

Several landforms on Mars have been suggested to be related to the presence of ground ice (Mangold 2003, Squyres 1978, Squyres & Carr 1986), including lobate debris aprons, concentric and lineated crater fill and fretted terrain (Colaprete & Jakosky 1998, Lucchitta 1984, Squyres 1978). These landforms are commonly related to the creep of ice and debris as documented from various latitudes and in a varying geologic context (Crown et al. 2003, Head et al. 2005, 2006, Mangold 2001, Mangold & Allemand 2001, Squyres 1979, van Gasselt et al. 2007).

Large-scale features at the Martian fretted terrain and so-called lobate debris aprons have been primary candidates for periglacial landforms, but the availability of high resolution image and topography data over increasingly large portion of the Martian surface has allowed discovery and exploration of smaller features, comparable in size to terrestrial rock glacier systems. Recent landforms interpreted as glacial or periglacial have been described extensively also at tropical to equatorial latitudes on Mars (Head et al. 2006, Rossi et al. 2000, van Gasselt et al. 2007, 2008) during the last decade.

Also, the presence of ground ice has been indirectly assessed on Mars with non-image data by instruments such as the Neutron Spectrometer onboard 2001 Mars Odyssey spacecraft (Feldman et al. 2004): the large-scale inventory of potential ice-rich deposits in Martian soil indicates regional high abundances of thick bodies of ground ice, especially at mid to high northern latitudes.

Data and Methods

In the present work we used image and topographic data from different sources: MGS (Mars Global Surveyor) MOLA (Mars Orbiter Laser Altimeter) topographic data, MEX (Mars Express) HRSC (High Resolution Stereo Camera), and 2001 Mars Odyssey THEMIS (Thermal Emission Imaging System). In selected areas, we also used THEMIS visible (VIS) and MGS MOC (Mars Orbiter Camera) narrow angle (NA) images. HRSC-derived digital elevation models have been used as well (Gwinner et al. 2005). HRSC data, with their high spatial resolution and large swath, are well complemented by very high resolution MOC NA data. MOLA topography has been used mostly in the form of single profiles (Precision Experiment Data Records, PEDR), in order to avoid any resampling effect introduced during data gridding, because of the small scale (few km) of several of the studied landforms; gridded MOLA Mission Experiment Gridded Data Records (MEGDR) data were used in areas where profiles could not be extracted.

The nomenclature used here is descriptive, trying to avoid genetic terms or implications whenever possible. The

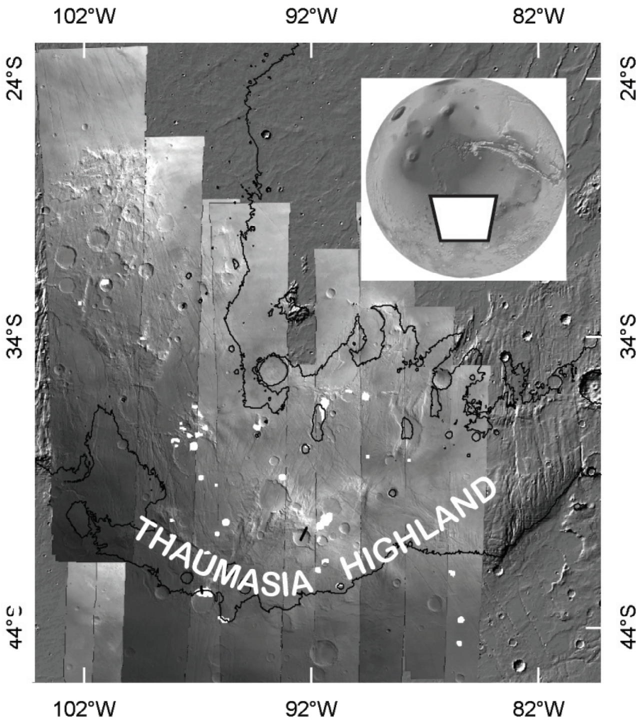

Figure 1. Location of possible periglacial landforms outlined in white, on top of HRSC Nadir Mosaic (Nadir channels from orbits 266, 279, 292, 344, 357, 380, 420, 431, 442, 453, 486, 497, 508, 530, 563) of Thaumasia Highland. The 4000 m altitude contour line is indicated in black; the background is a MOLA topography-based shaded relief.

terminology is similar to the one used by Whalley & Azizi (2003).

Thaumasia Geology and Geomorphology

The Thaumasia region on Mars located in the eastern hemisphere near 35° latitude is well known for its primarily volcanic and complex tectonic history (Fig. 1).

The Thaumasia region on Mars has a rich and complex geological history (Dohm et al. 2001, Dohm & Tanaka 1999). It comprises a tectonic plateau, characterized by high plains and dissected by various graben systems (Grott et al. 2007). In addition several smaller-scaled compressional tectonic features, such as wrinkle ridges (Dohm & Tanaka 1999) indicative of the volcano-tectonic history are observed frequently.

Among younger water-related surface features (Ansan & Mangold 2006), there is also an abundance of geomorphic evidence for cold-climate resurfacing processes such as a variety of periglacial landforms or glacial-like flows. Low latitude glacial or glacial-like morphologies have been described mostly from the northern hemisphere (Head et al. 2006), and recently also from the southern one (Dickson et al. 2006, Rossi et al. 2006),

The Thaumasia region was one of the areas on Mars where work on periglacial and glacial landforms is relatively sparse (Dickson et al. 2006, Rossi et al. 2006) which is predominantly caused by a substantial lack of high resolution data coverage (e.g., MOC) at the time when large-scale mapping efforts were started (Dohm et al. 2001).

Description of Study Area and Landforms

The study area spans in latitude from 25°S to 45°S. The altitude of identified ice-related landforms is more constrained, being in general higher than 4000 m above Mars MOLA datum with elevations as high as 5000 m. (Fig. 1).

Three main kinds of possible ice-assisted creep-related landforms have been found in Thaumasia Highland: lineated crater (and valley) fills, debris aprons, and protalus lobes.

Lineated crater fills

This group of features appears to be very widespread in the study area and was described initially from the northern dichotomy boundary and the southern-hemispheric impact basins (Squyres 1978, 1979).

There is a high abundance of impact craters larger than a few kilometers in diameter that show this peculiar surface texture in Thaumasia Highland.

Lineated crater and valley fills are usually associated to each other and form curvilinear ridges and saddles, usually arranged with slightly concentric to transversal geometries (Figs. 2A, 2C). Longitudinal ridges, similar to the ones present in fretted terrains (Squyres 1978) are usually not observed. Lineations appear as ridges and furrows arranged transversally with respect to the inferred flow direction. The surface texture of lineated fills is relatively rough. Circular to sub-circular features, possibly being degraded small impact craters (Fig. 2C) are visible within the infill. The lack of high-resolution data (e.g., in Fig. 2C) does not allow generalizations over the complete population of lineated craters. Circular to irregular depressions with unclear impact origin are also abundant in crater fills: they show a certain resemblance with thermokarst features (Costard & Kargel 1995).

Lineated and/or curvilinear crater fills on Mars have been interpreted as related to ice flow (Squyres & Carr 1986), or were alternatively attributed to eolian erosion (Zimbelman et al. 1989).

Most lineated fills are showing general slopes consistently with flow directions derived from morphology (Figs. 2A, 2B). The direction of flows in these crater fills shows a correlation to regional slope orientation but little to no connection to local exposure, unlike protalus lobes features as described below.

The actual thickness of these fills in not well constrained, since they appear completely contained within crater rims and no cross-section cuts are visible in the study area.

Debris aprons

Certain craters in the Thaumasia Highland are showing features with a strong resemblance with debris aprons (Colaprete & Jakosky 1998, Squyres 1978, Squyres & Carr 1986) (Fig. 3B). They are isolated or appear superimposed on lineated crater fills. These landforms often show concave upward profiles

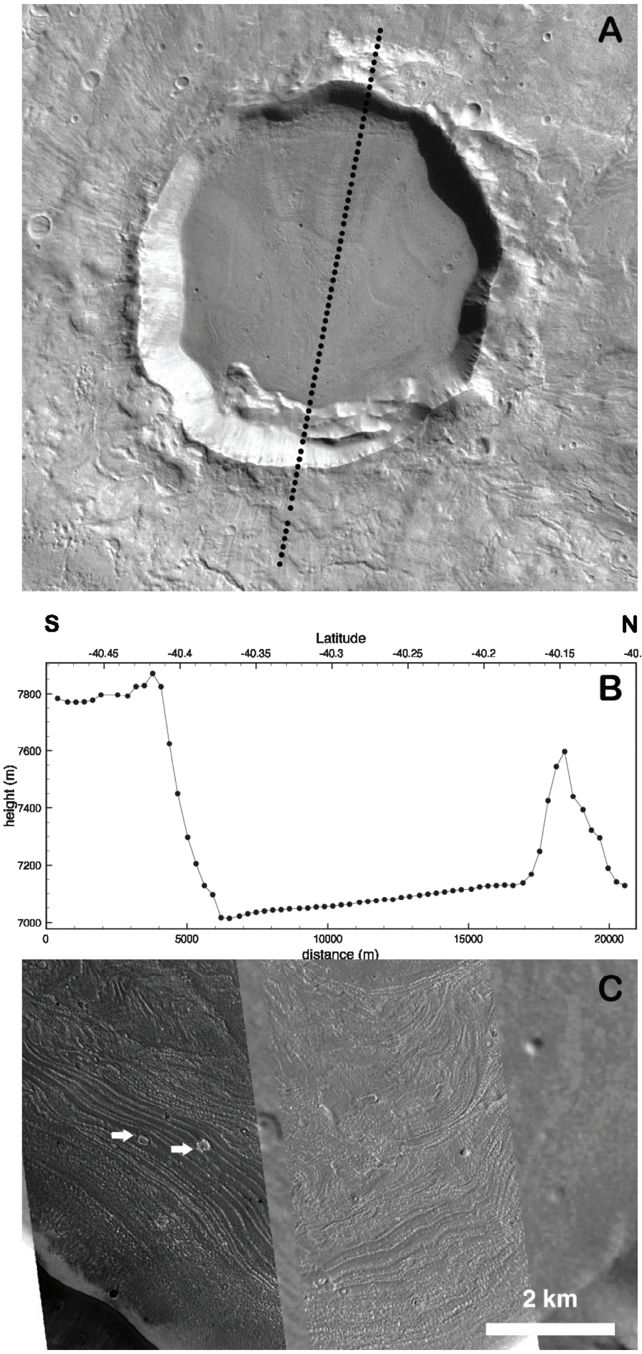

Figure 2. A) HRSC nadir from orbit 442 (north is up), the footprints of MOLA PEDR shots are indicated by black dots; the scene is about 20 km wide. The flow-like lineated crater fill is mainly emanating from the northern part of the crater. B) Portion of MOLA profile from orbit 19873: the lineated crater fill has an almost constant slope of about 0.5° southwards. C) Detail of the morphology of a lineated crater fills at MOC scale (HRSC orbit 508, MOC NA E1200147 and E0501814). Arrows indicate sample deformed (compressed) crater-like features embedded in the crater fill.

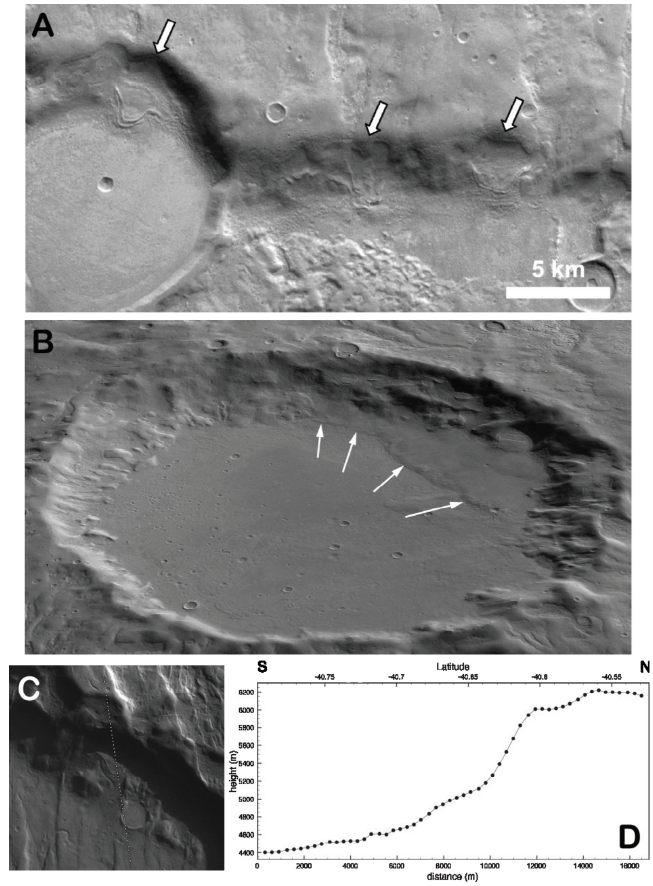

Figure 3. A) Example of well-developed protalus lobes, indicated by arrows (HRSC nadir band from orbit 292, north is up). These lobate forms are developed on crater floors or fills and linear slopes. B) perspective view of HRSC nadir from orbit 453 draped on HRSC stereo-derived DTM (Gwinner et al. 2005). Arrows indicate the edge of a concave debris apron. Small, apparently younger protalus lobes are located on the highest part of the rim, well above the debris apron. C) HRSC nadir from orbit 508, the footprints of MOLA profile shown in 3-D are indicated; the protalus lobe is facing southward and it's largely in shadow; the image is about 25 km wide; the lobate feature is about 5 km long; north is up D) Portion of MOLA PEDR profile from orbit 13002: The protalus lobe in 3C shows a convex upward profile, unlike some debris aprons such as the one in 3B. The inferred thickness for this particular lobe is about 200 m.

on MOLA and HRSC DTM (Gwinner et al. 2005) contrasting to large-scale features observed at the dichotomy boundary which usually are convex upward (Chuang & Crown 2005, Mangold & Allemand 2001, Squyres 1978, van Gasselt et al. 2008). They are characterized by smooth to moderately rough surface texture. Both in term of scale, apparent chronology, and degradation level, they appear to be transitional between larger, older lineated crater fills and smaller protalus lobes. They tend to emanate from south-facing slopes, but with a less clear correlation to the general direction of exposure when compared to protalus lobes.

Protalus lobes

Protalus lobes (Whalley & Azizi 2003) are the most common possible periglacial landform which could be found in the study area. They are characterized by multiple lobate concentric ridges. Their width usually exceeds their length (Figs. 3A, 3C), thus forming broad features along footslopes. Their total length is in most cases limited to few kilometers and few of them are just 2 to 3 km long (Fig. 3A).

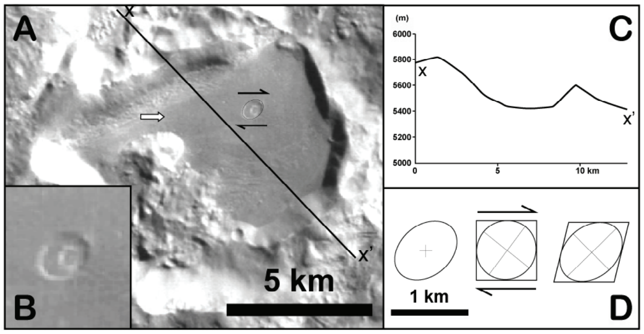

Figure 4. A) Example of possible finite strain of an originally circular impact crater. The black arrows symbolize the simple shear direction, and the white one indicates the directions of linear features in the crater fill with an azimuth consistent with the simple shear inferred by the elliptical crater-like feature; HRSC orbit 497. B) Enlargement of the apparently deformed circular feature (impact crater?) C) Topographic profile across the valley fill imaged in 4A from MOLA gridded topography: the local slope is consistent with the inferred direction of movement and the observed finite strain. D) Strain of a supposed originally circular impact crater under simple shear, hypothesized in this case.

Their texture is moderately rough as observed at scales of HRSC (~15–20 m/pixel resolution) and MOC (~3–5 m/pixel resolution): where high-resolution MOC image data are available, their surface even appears blocky.

Protalus lobes develop preferentially on south-facing slopes, both in case of linear south-facing scarps and northern impact crater rims. The apparent flow direction is from north to south. The correlation between exposure and development for protalus lobes is much stronger than for any other landforms discussed herein.

The impact crater density on these lobate landforms is very scarce: it is the lowest among all morphologies described here. This is also consistent with the observed geometrical relationship between all the different possible periglacial landforms in Thaumasia.

The thickness of protalus lobes can be evaluated using MOLA PEDR profiles: thicknesses range from a few tens of meters up to approximately 200 m (Fig. 3D).

In addition, features similar to protalus ramparts (Whalley & Azizi 2003) have been observed in various parts of Thaumasia Highland (Fig. 3). They appear less widespread than lobes. They tend to develop on top of other larger flow features, such as lineated valley fills.

Morphometric aspects—finite deformation of fills

Both MOLA altrimetric data (single profiles) and HRSC-derived DTM data have been used to characterize the morphology and morphometry of landforms in the Thaumasia Highland.

Crater fills are characterized by very gentle slopes, consistent with the flow direction that could be derived from morphological observations (Fig. 2). The slopes are usually less than one degree. The slopes of crater fills imaged in Fig. 2 are averaging at 0.6 degrees dipping southward. The more convex portion of protalus lobes shows a slope inclination of up to about 7 degrees (Fig. 3D).

Apart from the local disruption and deformation (Fig. 2C), some lineated crater fills show evidence of horizontal deformation/movement. In one case (Fig. 4), it was possible to measure finite deformation of a presently elliptical feature, interpreted as a deformed impact crater (Fig. 4B). Linear features in the crater fill units (Fig. 4A) show a direction consistent with horizontal simple shear, as deduced from the deformation of an original circular impact crater (Fig 4B). The simple shear deformation assumes area conservation on the surface of the fill, which appears to be a reasonable assumption. The assumption of an original circularity of the structure in Fig. 4B is also consistent with the observed crater features (at available resolution), which are ruling out an oblique impact event (an alternative explanation for such an oblique structure), because a hypothetical projectile with a 5–10 degrees incidence angle, needed to produce such an elliptical crater (Gault & Wedekind 1978), would impact on the outer rim before reaching its interior (Fig. 4C).

The finite maximum linear deformation (and linear movement within the fill) of the crater is of about 200 meters. The timescale is not well constrained. Also, the thickness of the deformed fill (and the vertical component of the deformation) is not well constrained.

Relative chronology

Lineated valley/crater fills appear to be the oldest feature among the ones described in the present study. Debris aprons and, later, protalus lobes are characterizing the most recent landscape evolution in the Thaumasia Highland area.

The relative chronology of the landforms in the study area indicates progressive shrinking of landforms confirming the ideas of ice-assisted creep and flow. This view is consistent with considerations of the preservation of morphologies and the local stratigraphic relationships (protalus lobes are clearly postdating lineated crater fills.).

Lineated crater fill units appear often from poorly to slightly altered by crater impacts. At several places, these units have a slightly deflated appearance, which suggests that the present fretted appearance is related partially to erosive effects, also suggesting again an older age of lineated crater/valley fills when compared to protalus ramparts and lobes.

Discussion and Conclusions

Our analysis shows distinct landform development through time in Thaumasia Highland. A generic sequence of periglacial landform development in the study area includes, in chronological order:

a) Large lineated crater fills (areas of ~150–170 km^2), containing possible thermokarst features.
b) Moderate debris aprons (areas of several tens of km^2), with a general “deflated” appearance.
c) Small protalus lobes with little to no impact craters visible at available image resolutions (lengths of ~2–5 km).

d) Locally very small protalus ramparts (several hundred meters to few kilometers in size).

Crater-size frequency analyses to deduce absolute ages will produce unreliable absolute ages due to high degradational effects as well as due to flow deformation of surfaces. The very small size of discovered protalus lobes makes absolute dating even more difficult. Geometrical and stratigraphic relationships are in any case showing a sensibly more recent age of small protalus lobes with respect to lineated crater/valley fills.

Also, the size of these two main groups of landforms is very different: lineated (and sloping) crater fills are large, up to more than 100 km^2, while protalus lobes are usually covering areas of not more than 5–10 km^2.

The flow direction inferred from lineated crater fills show little to no correlation with slope orientation, being more correlated with local and regional topography. On the other hand, mostly concave-upward debris aprons and mostly convex-upward protalus lobes are developed preferentially on south-facing slopes, suggesting a stronger and temporarily closer role of morpho-climatic conditions during their development. This is consistent with previous observations on glacial/periglacial features at mid to low-latitudes (Head et al. 2005).

In the Thaumasia highlands, the dominant concave-upward profile of debris aprons (Mangold & Allemand 2001, Squyres 1978), where present, is indicative of a past scenario involving the melting of ice-cored rock glaciers or debris-covered glaciers (Clark et al. 1994). Contrasting to this, protalus lobes mostly show clear convex-upward profiles (Fig. 3D), which together with their apparent relatively young age is indicating that they might have been active recently or might even be active today.

Although the nature and evolution of such landforms are often controversially discussed, there is observational evidence that the existence and evolution of such landforms is related to climatic variations controlled by the orbital configuration of Mars (Forget et al. 2006, Laskar et al. 2004, Murray et al. 1973, Ward 1974), which was responsible for the deposition of equatorial ice during high-obliquity phases and depletion of an ice reservoir during periods of low obliquities.

The Thaumasia highlands provide the geomorphologic settings necessary for formation of creep-related landforms due to an abundance of high-relief slopes and tectonically dissected terrain allowing accumulation and supply of wall-rock debris at footslopes.

We identified flow and creep morphologies exhibiting a lobate to tongue-like shape and which are characterized by linear to curvilinear ridges and furrows closely resembling large-scale gelifluction lobes or terrestrial rock glaciers and protalus landforms indicative of periglacial environments.

The general lack of impact craters suggests young surface ages. Although water ice is not considered to be stable at equatorial latitudes on Mars today, there are morphologic indicators suggesting re-activation and/or even initial formation of such landforms in the transitional belt between equatorial latitudes and mid-latitudes on Mars during geologically recent times.

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References

Ansan, V. & Mangold, N. 2006. New observations of Warrego Valles, Mars: Evidence for precipitation and surface runoff. *Planetary and Space Science* 54: 219-242.

Chuang, F.C. & Crown, D.A. 2005. Surface characteristics and degradational history of debris aprons in the Tempe Terra/Mareotis fossae region of Mars. *Icarus* 179: 24-42.

Clark, D.H., Clark, M.M. & Gillespie, A.R. 1994. Debris-covered glaciers in the Sierra Nevada, California, and their impications for snowline reconstructions. *Quaternary Research* 41: 139-153.

Colaprete, A. & Jakosky, B.M. 1998. Ice flow and rock glaciers on Mars. *Journal of Geophysical Research* 103: 5897.

Costard, F.M. & Kargel, J.S. 1995. Outwash plains and thermokarst on Mars. *Icarus* 114: 93-112.

Crown, D.A., McElfresh, S.B.Z., Pierce, T.L. & Mest, S.C. 2003. Geomorphology of debris aprons in the Eastern Hellas region of Mars. *Lun. Planet. Sci. Conf. Abs.* League City, Houston, Tex., USA: Lun. Planet. Inst., 1126. CD-ROM.

Dickson, J.L., Head, J.W., Kreslavsky, M.A. & Marchant, D.R. 2006. Linear Lobate Debris Aprons, Piedmont-like Lobes, and Crater Fill in the Acheron Fossae Graben Region, Mars: Evidence for Debris-covered Glacier Formation and Flow. *37th Annual Lunar and Planetary Science Conference, Volume 37*: 1321.

Dohm, J.M. & Tanaka, K.L. 1999. Geology of the Thaumasia region, Mars: plateau development, valley origins, and magmatic evolution. *Planetary and Space Science* 47: 411-431.

Dohm, J.M., Tanaka, K.L. & Hare, T.M. 2001. *Geologic Map of the Thaumasia Region, Mars.* Map I-2650, Geologic Investigation Series. U.S. Department of the Interior, U.S. Geological Survey.

Feldman, W.C., Prettyman, T.H., Maurice, S., Plaut, J.J., Bish, D.L., Vaniman, D.T., Mellon, M.T., Metzger, A.E., Squyres, S.W., Karunatillake, S., Boynton, W.V., Elphic, R.C., Funsten, H.O., Lawrence, D.J. & Tokar, R.L. 2004. Global distribution of near-surface hydrogen on Mars. *Journal of Geophysical Research (Planets)* 109: 09006, doi: 10.1029/2003JE002160.

Forget, F., Haberle, R.M., Montmessin, F., Levrard, B. & Head, J.W. 2006. Formation of Glaciers on Mars by

Atmospheric Precipitation at High Obliquity. *Science* 311: 368-371.

Gault, D.E. & Wedekind, J.A. 1978. Experimental Studies of Oblique Impact. *Lunar and Planetary Institute Conference Abstracts* 9: 374-376.

Grott, M., Kronberg, P., Hauber, E. & Cailleau, B. 2007. Formation of the double rift system in the Thaumasia Highlands, Mars. *Journal of Geophysical Research (Planets)* 112: 06006, doi: 10.1029/2006JE002800.

Gwinner, K., Scholten, F., Spiegel, M., Schmidt, R., Giese, B., Oberst, J., Jaumann, R., Neukum, G. & Team, H.C.-I. 2005. Hochauflösende Digitale Geländemodelle auf der Grundlage von Mars Express HRSC-Daten: *Photogrammetrie– Fernerkundung–Geoinformation* 5: 387-394.

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. & Co-Investigator Team, T.H. 2005. Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars. *Nature* 434: 346-351.

Head, J.W., Marchant, D.R., Agnew, M.C., Fassett, C.I. & Kreslavsky, M.A. 2006. Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change. *Earth and Planetary Science Letters* 241: 663-671.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B. & Robutel, P. 2004. Long term evolution and chaotic diffusion of the insolation quantities of Mars. *Icarus* 170: 343-364.

Lucchitta, B.K. 1984. Ice and debris in the fretted terrain, Mars. *Journal of Geophysical Research* 89: 409.

Mangold, N. 2001. Lobate Debris Aprons as Potential Targets for Ground Ice Detection Analogs to Terrestrial Rock Glaciers. *Conference on the Geophysical Detection of Subsurface Water on Mars*, 7009.

Mangold, N. 2003. Geomorphic analysis of lobate debris aprons on Mars at Mars Orbiter Camera scale: Evidence for ice sublimation initiated by fractures. *Journal of Geophysical Research (Planets)* 108: 8021.

Mangold, N. & Allemand, P. 2001. Topographic analysis of features related to ice on Mars. *Geophysical Research Letters* 28: 407-410.

Murray, B.C., Ward, W.R. & Yeung, S.C. 1973. Periodic insolation variations on Mars. *Science* 180: 638-640.

Rossi, A.P., Komatsu, G. & Kargel, J.S. 2000. Rock Glacier-like Landforms in Valles Marineris, Mars. *Lunar and Planetary Institute Conference Abstracts* 31: 1587.

Rossi, A.P., Chicarro, A.F., Pacifici, A., Pondrelli, M., Helbert, J., Benkhoff, J., Zegers, T., Foing, B. & Neukum, G. 2006. Widespread Periglacial Landforms in Thaumasia Highland, Mars. *37th Annual Lunar and Planetary Science Conference*, *Volume 37*: 1568.

Squyres, S.W. 1978. Martian fretted terrain–Flow of erosional debris. *Icarus* 34: 600-613.

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

Squyres, S.W. & Carr, M.H. 1986. Geomorphic evidence for the distribution of ground ice on Mars. *Science* 231: 249-252.

van Gasselt, S., Hauber, E. & Neukum, G. 2007. Cold-climate modification of Martian landscapes: A case study of a spatulate debris landform in the Hellas Montes Region, Mars. J*ournal of Geophysical Research (Planets)* 112: 09006, doi: 10.1029/2006JE002842.

van Gasselt, S., Hauber, E., Rossi, A.P. & Neukum, G. 2008. Emplacement of lobate rock glacier landforms and landscape modifications, Mareotis Fossae, Mars. *Proceedings of the Ninth International Conference on Permafrost, Fairbanks, Alaska, June 29–July 3, 2008* (this proceedings).

Ward, W.P. 1974. Climate Variations on Mars, 1, astronomical theory of insulation. *Journal of Geophysical Research* 79: 3375-3386.

Whalley, W.B. & Azizi, F. 2003. Rock glaciers and protalus landforms: Analogous forms and ice sources on Earth and Mars. *Journal of Geophysical Research (Planets)* 108d, doi: 10.1029/2002JE001864.

Zimbelman, J.R., Clifford, S.M. & Williams, S.H. 1989 Concentric crater fill on Mars – an aeolian alternative to ice-rich mass wasting. *19th Lunar and Planetary Science Conference, Houston, TX*. Houston, TX Lunar and Planetary Institute, 397-407.