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Abstract: Possible periglacial and relict glacial landforms in the ancient mountain range of the Thaumasia Highlands, Mars, are described. The landforms include large-scale mantling, lineated crater and valley-fill materials, debris aprons, protalus lobes and ramparts. The most pristine ice-related landforms appear to be small-scale protalus lobes and ramparts with no visible distinct impact craters at both medium (High Resolution Stereo Camera (HRSC)) and high (Mars Orbiter Camera (MOC) narrow angle (NA), Context Camera (CTX)) spatial resolution. These small landforms are possibly active at present and post-date more extensive features such as crater fills, possibly formed during high obliquity climatic periods.

In contrast to the rock glacier-like landforms with distribution preferentially occurring on south-facing slopes, possibly controlled by enhanced exposure to the Sun, older, less pristine lineated fill materials show a less systematic distribution of flow directions, suggesting a more generalized periglacial and possibly glacial environment in the Thaumasia Highlands.

Background

The possible presence of glacial (Kargel & Strom 1992) and periglacial (e.g. Squyres 1978; Lucchita 1981; Rossbacher & Judson 1981) features on Mars has been proposed and discussed since the Viking Orbiter missions era using relatively low-resolution Viking images. A system of glacial-like landforms extending from the south polar region into the Hellas impact basin, for example, was interpreted as marking ice-sheet-related activity (Kargel & Strom 1992). In addition to the Hellas glacial system, which was highly controversial, the fretted terrain (e.g. Squyres 1978) and the debris aprons, interpreted as some form of rock glacier (Colaprete & Jakosky 1998), were the main candidates for ice-related landforms during the era.

Post-Viking missions data have significantly increased the number of identified ice-related landforms, including candidate rock glaciers, which indicates climatic and environmental conditions vastly different to those observed today. This increase in data is thanks in part to high-resolution Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) imagery (Rossi et al. 2000). Most periglacial landforms were simply not easily visible at resolutions lower than the ones achieved, in the first instance, by MGS. In addition, several ice-related landforms appear to have formed during recent geological times through the evaluation of the post-Viking-era data (e.g. Head & Marchant 2003).

With this new-found perspective on ice-related modifications to the Martian landscape and the resulting enhanced enquiry by the planetary science community, Whalley & Azizi (2003) pointed to problems in the description of both terrestrial and Martian rock glaciers, including nomenclature and formational mechanisms. Likewise, Mahaney et al. (2006) discussed in detail the investigation of rock glaciers on Earth and their Martian counterparts.
Other relevant post-Viking-era observations included in the literature are the presence of ground ice at relatively shallow depths (Boynton et al. 2002, 2004; Feldman et al. 2002, 2004) and at increasingly lower latitudinal reaches through time (e.g. Head & Marchant 2003; Head et al. 2006; Dickson et al. 2008; Hauber et al. 2008). Similarly, several glacier or rock glacier-like landforms have been discovered in tropical latitudes (e.g. Head & Marchant 2003) which are interpreted as being debris-covered glaciers.

Low-latitude glacial-like morphologies have been documented mostly in the northern hemisphere (Head et al. 2006), but recently have also been found in the southern hemisphere (Berman et al. 2005, 2009; Dickson et al. 2006; Rossi et al. 2006, 2008).

With regard to these features newly identified through the analysis of post-Viking data, the Thaumasia Highlands region was one of the geological provinces on Mars with very few reported (Dickson et al. 2006; Rossi et al. 2006, 2008) glacial–periglacial features despite the rich and complex geological history of the region (Dohm & Tanaka 1999; Dohm et al. 2001b). Therefore, the present work attempts to fill a gap in describing possible periglacial–glacial landforms on Mars, specifically within the high-altitude, ancient mountain range of the Thaumasia Highlands region. Such rugged environments have the potential to yield further clues concerning the palaeoclimatic and palaeoenvironmental conditions of Mars.

In addition to transient endogenic-driven activity and the associated change in climate and environmental conditions that resulted in a landscape modified by water–ice and liquid water (Baker 2001), geologically recent obliquity-driven climatic changes and the associated precipitation have been proposed as the driving forces for the development of glacial–periglacial landforms on Mars (Forget et al. 2006). In particular, some model runs also show the growth of ice at high altitudes such as in the Thaumasia Highlands region and its surroundings (Madeleine et al. 2007), the region where the present work concentrates.

**Thaumasia settings**

The Thaumasia Highlands (Fig. 1) is a rugged ancient mountain range on Mars (Dohm et al. 2001a, b), which separates the Tharsis magmatic complex (Dohm et al. 2001a, 2007) to the NNW from the Argyre impact-influenced transition zone to the SSE. The highest promontory within the mountain range is Warrego Rise (268°E, 40°S) at an elevation of more than 7.6 km above Martian datum. Therefore, there is a significant difference in elevation between the Thaumasia Highlands region and its surrounding area (e.g. the floor materials of the Argyre Basin, for example, occur below the –2 km Martian datum), and this possibly exerts a significant influence on the regional environmental–climatic conditions.

The distinct Warrego Rise is located near the southernmost margin of the Thaumasia Highlands. Heat flow calculations indicate that the crust beneath the rise may be chemically stratified, with a heat-producing enriched upper layer thinner than the whole crust (Ruiz et al. 2009). Stratigraphic and cross-cutting relations, impact-crater statistics, an order of magnitude greater density of tectonic structures in the Noachian mountain-forming materials compared to the Late Hesperian lava plains of the shield complex of Syria Planum, and magnetic signatures indicate that the mountain range formed during an ancient geological period of Mars, prior to the shut down of the magnetosphere (Dohm et al. 2001a, b, 2009).

Faults and folds of diverse orientation resulting from contractional and extensional deformation, complex rift systems, shield volcanoes that occur along rift systems, and hogbacks, cuestas and valley networks such as Warrego Valles (267°E, 42°S), record a complex geological history for the Thaumasia Highlands region (Dohm & Tanaka 1999; Dohm et al. 2001a, b, 2007; Grott et al. 2005, 2007; Hauber & Kronberg 2005; Anguita et al. 2006), which may include magmatic-driven activity such as igneous plateau uplift (Dohm et al. 2001b) and possibly some form of plate tectonism (Dohm et al. 2002; Anguita et al. 2006; Baker et al. 2007). Contrary to such a complex history, a gravity-spreading system (mega-slide) related to the geothermal heating and topographical loading of extensive buried deposits of salts and/or mixtures of salts, ice and basaltic debris has been proposed to explain the formation of the Thaumasia Highland mountain range (Montgomery et al. 2009).

To date, the parent mountain-forming rock materials of the Thaumasia Highlands are unknown, perhaps largely due to secondary weathering rinds, aeolian mantles, alluvial fans, fluvial deposits and periglacial materials. The latter of these, which is the primary focus of this study, obscures the bedrock materials from an orbital perspective (Dohm et al. 2009). Thermal Emission Spectrometer (TES)- and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)-based analyses indicated spectral signatures distinct from the volcanic lava flows of the shield complex of Syria Planum, which includes phyllosilicates (Dohm et al. 2009). Based on the features similar to terrestrial mountain ranges, parent rock materials in addition to basalt and basaltic andesites are anticipated (Scott & Tanaka 1986; Dohm et al. 2009).

When a regional mapping investigation of the Thaumasia Highlands region and surrounding area...
was carried out (Dohm et al. 2001b) the relatively small-scale landforms such as the ones described here were not distinct enough to be resolvable using the Viking Orbiter imagery. Our focused survey (Rossi et al. 2006, 2008) of possible ice-related landforms in the region has been enhanced with the use of more recent higher-resolution imagery and topographical data.

Data and methods

In this study we use image data from multiple missions, including: MGS Mars Orbiter Laser Altimeter (MOLA) topographical data; both Mission Experiment Gridded Data Records (MEGDR) grids (128 pixel/degree) and Precision Experiment Data Records (PEDR) profiles (c. 200 m ground spacing between shots); Mars Express (MEX) High Resolution Stereo Camera (HRSC); and 2001 Mars Odyssey (MO) Thermal Emission Imaging System (THEMIS). In selected areas we also utilize THEMIS visible (VIS), MGS MOC narrow angle (NA), Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) and MRO High Resolution Imaging Science Experiment (HiRISE), where available.

In addition, topographical data derived from HRSC stereo imagery were used. In particular, a custom multi-orbit digital elevation model (DEM) was produced (e.g. Gwinner et al. 2005; Dumke et al. 2008), based on stereo imagery form MEX HRSC orbits 420, 431, 442, 453, 486, 497, 508 and 530 with a final ground resolution of 125 m per pixel (Fig. 2).

The data were processed with either DLR-VICAR (Video Image Communication and Retrieval, produced by the Jet Propulsion Laboratory and modified by the German Space Agency, DLR) or the United States Geological Survey (USGS) Integrated Software for Imagers and Spectrometers.

Fig. 1. Location map. HRSC nadir mosaic over MOLA-based shaded relief map. The coverage of the imagery mosaic coincides with the extent of the HRSC stereo-derived 125 m per pixel DEM, obtained from orbits 420, 431, 442, 453, 486, 497, 508 and 530. Image credit: NASA/JPL/MOLA Science Team and ESA/DLR/FUB; see prelim viii for acronym definitions.
ISIS3 (Gaddis et al. 1997; Torson & Becker 1997; Anderson et al. 2004) system, and then integrated and analysed using geographical information systems (GIS) tools. The nomenclature used here is descriptive, trying to avoid genetic terms or implications when possible. The terminology is similar to the one used by Whalley & Azizi (2003).

Landforms described here are usually too small to provide reliable dating with crater counting (Wagner et al. 1999). Some of the landforms lack high-resolution coverage. Moreover, where suitable imagery is available, the identification of actual impact craters, often deformed, degraded or modified, among other topographic lows, such as thermokarst features, is difficult, if not unfeasible.

Geologically recent periglacial landforms in the Thaumasia Highlands region

Focusing on the rugged ancient mountain range of Thaumasia Highlands using post-Viking data as highlighted earlier, we have newly identified a suite of periglacial landforms that mark changes in climate and environmental conditions in a high-altitude environment of Mars. The features identified using post-Viking data includes plateau mantling features, lineated crater/depression-fill materials, debris aprons, protalus lobes and ramparts, as well as their association in space and time as described below.

Plateau mantling

Located outside of the impact craters and other topographical depressions, including grabens (Fig. 3a, b, e), terrain comprised mainly of plateau-forming materials appears to be highly mantled (Mustard et al. 2001; Kreslavsky & Head 2003; Milliken et al. 2003; van Gasselt et al. 2008). The altitude of these plateaus is largely 4000 m above Martian datum (Figs 1 & 2). The plateau surfaces appear to be smooth in places, in contrast to the rough pitted terrains that often occur in a close spatial relationship (Fig. 3f).
The mantles of materials are widespread but probably heterogeneous in thickness and preservation, covering pre-existing topography and relatively small impact craters. Such materials embay the rims of the larger degraded impact craters. Typical lineated fill materials characterize the interiors of these larger impact craters. The widespread mantles of materials may be the result of a combination of geological processes through time, including fluvial, alluvial, colluvial and glacial/ice-sheet deposition.

**Lineated crater/depression-fill materials**

Lineated crater/depression-fill materials (e.g. Dickson et al. 2008), similar to the fretted terrain (e.g. Squyres 1978; Lucchitta 1984) mainly observed in the northern hemisphere in the vicinity of the crustal dichotomy boundary, are widespread in the study area.

Most relatively large impact craters (Figs 2–4) in the highlands contain lineated (either transversal or subconcentric) fill materials; longitudinal textures, however, have not been identified in the study area.

Lineated, textured, pitted crater and depression-fill materials appear to be associated with each other. Within the fill materials, for example, ridges and saddles at lower spatial resolution (e.g. HRSC) appear to be composed of smaller-scale knobs and pits at higher resolution (e.g. CTX). The envelope of these small knobs is arranged slightly concentric to transversal ridges and furrows with respect to the inferred direction of flow(s) geometries (Fig. 3c, d). Unlike the fretted terrains, which occur in elongated depressions (e.g. Squyres 1978), longitudinal ridges are not observed.

At high resolution (decametre/metre scale; e.g. CTX/MOC) the surface texture of lineated fills is very rough. Circular–quasi-circular features, many of which could be small, degraded impact craters (Fig. 3a–d), are visible within the infill materials of various impact craters. These circular features are more widespread and numerous than expected based on analyses using lower-resolution data (Rossi et al. 2008). Some are likened to features elsewhere on Mars that have been interpreted to be thermokarst features (Costard & Kargel 1995) in the Chryse and Elysium areas. They include closed irregular depressions. Other lineated (either linear or curvilinear) fill materials on Mars (e.g. Dickson et al. 2008) have been interpreted to be the result of ice flow or eolian erosion (Zimbelman et al. 1989).

In most cases the topography of lineated fill materials is consistent with flow directions inferred from morphology and texture (Figs 3 & 4). The flow directions of these crater-fill materials correlate with regional slope, but with little or no correlation to local exposure, unlike protalus lobes and ramparts (Figs 5 & 6) (Berman et al. 2005, 2009). The slopes of the lineated fill materials are usually less than 1°, as exemplified in two examples (Fig. 4) with average slopes of 0.6° (Fig. 4c, d) and 0.5° (Fig. 4e, f).

The thickness of the fill materials is difficult to determine in the study area because they are enclosed by impact-crater walls or depression-boundary scarps with no observed natural cuts that expose total cross-sections of the materials. However, there are minor fault scarps visible in places within the lineated valley fills with noticeable offsets (Fig. 3f). Although, it is not clear whether these fault scarps post-date or predate the fill materials. In the latter case, the faults may have been covered by material that was subsequently partially sublimated, leaving behind a lag and an exhumed fault.

Apart from local disruption and deformation (Fig. 3a–d), some lineated fill materials show evidence of horizontal deformation/movement. In one case (Fig. 7) the finite deformation of an elliptical feature, interpreted to be a deformed circular impact crater (Fig. 7a, b), can be measured. Linear features in the impact-crater fill materials (Fig. 7a) indicate a direction (indicated with a white arrow in Fig. 7a) consistent with horizontal simple shear (black in Fig. 7c), as deduced from the deformation of an assumed circular impact crater, rather than pure shear (light grey in Fig. 7c). The simple-shear deformation assumes area conservation on the surface of the fill. The assumption of an original circular impact crater in Figure 7c is also consistent with the observed crater features (at available resolution) that tend to rule out an oblique impact event (an alternative explanation for such an oblique structure). A hypothetical projectile with a 5°–15° incidence angle (Gault & Wedekind 1978) necessary to produce such an elliptical crater would probably impact on the outer rim before reaching its interior (Fig. 7d). Also, a thin-rimmed structure, as observed in Figure 7b, which has a major axis length of about 800 m does not display features of a non-impact origin, such as pingos. Moreover, the lineations in the textured floor, although not imaged in very high resolution, seem to be consistent with a direction of movement compatible with simple shear and are marked by a white arrow in Figure 7a. The finite maximum linear deformation (and linear movement within the fill) of the crater is of about 200 m. Both the thickness of the deformed fill materials and the vertical component of the deformation cannot be determined. Such a deformation, if confirmed, would provide an unambiguous determination of actual movement in lineated valley-fill materials. Moreover, although
Fig. 3. Lineated valley fill at different scales. North is up for all images. (a) Slightly deflated, pitted lineated crater fill (CTX P16_007246_1406_XI_39S094W). ‘T’ indicates possible thermokarst-like depressions within the crater fill; ‘M’ indicates mantling. (b) Heterogeneous crater fill: lineated very pitted/blocky on the northern part. ‘R’ indicates ridges, possibly indicated past higher topographic levels of the fill; ‘M’ indicates mantling. (CTX P16_007246_1406_XI_39S094W). (c) Thinly spaced multiple lineations in a crater fill. ‘R’ indicates ridges. (CTX P13_006191_1456_XN_34S089W); the extent of (d) is outlined in white. (d) Detail from (c): multiple lobes of ridged material are visible,
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Fig. 3. (Continued) with highly compressed portions of the fill at their junction; several crater-like depressions are present (CTX image as in c). (e) Example of mantled plateau and fretted-like terrain in the lowlands, separated by a normal fault scarp. ‘M’ indicates mantling and ‘EM’ etched mantling, possible modified by sublimation and/or eolian erosion. Very smooth and highly pitted terrains are co-existing in the mantled units (CTX P16_007246_1406_XI_39S094W). (f) Normal fault in a lineated crater fill: it is not clear whether the fault precedes the deposition, movement and likely sublimation of the deposits or not (CTX P16_007246_1406_XI_39S094W). Image credit: NASA/JPL/MSSS.

Fig. 4. HRSC DEM topography of lineated crater fills. (a) 25-m vertical spacing contour map over a lineated crater (thick lines every 100 m) the same crater is imaged in (c) and the extent of (a) is outlined in (b) (HRSC DEM, 125 m/pixel). (b) Local setting of crater in (a) outlined in semi-transparency (HRSC nadir mosaic, overlain by 500 m vertical spacing HRSC DEM contours). (c) HRSC nadir image (orbit 497) and the outline of the topographical profile. (d) HRSC nadir image (orbit 442) over another lineated crater. (e) HRSC DEM topographical profile outlined in (c). (f) HRSC DEM topographical profile outlined in (e). Image credit: NASA/JPL/MOLA Science Team and ESA/DLR/FUB.

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the size of affected areas is rather small and high-resolution imagery is lacking in that particular spot, being able to date the fill would possibly also provide a strain-rate estimate.

**Debris aprons**

Landforms displaying similar morphologies to debris aprons observed elsewhere on Mars (e.g. Crown *et al.* 2003; Mangold 2003; van Gasselt *et al.* 2008) are present in some of the impact craters in the Thaumasia Highlands region (Fig. 5a). They are isolated or appear superimposed on lineated crater floors or fill materials (Fig. 5a).

Debris aprons in the Thaumasia Highlands region are characterized by smooth to moderately rough surface textures. In terms of scale, apparent chronology and degradational state, they appear to be transitional between larger older lineated fill materials and smaller protalus lobes. They tend to emanate from south-facing slopes, but with less distinct correlation to the general direction of exposure when compared with protalus lobes.

These landforms often show concave-upwards profiles on MOLA and HRSC DTM, in contrast to large-scale features observed at the dichotomy boundary that are usually convex upwards (e.g. Mangold 2003).

The thickness of the debris apron shown in Figure 5a is nearly 200 m, as estimated by prolonging the curvature of the slope/floor below the apron itself. Debris aprons in the Thaumasia Highlands region are far fewer in number compared with other parts of Mars, which is especially highlighted at northern latitudes (e.g. Crown *et al.* 2003; Mangold 2003; van Gasselt *et al.* 2008).
Protalus lobes (Shakesby 1997) are commonly found in the study area in close association with impact-crater rims and, in general, fault scarps resulting from compressional or extensional deformation. The lobes are characterized by multiple lobate concentric ridges with a relatively simple geometry when compared with the fill materials described in the subsection on ‘Lineated crater/depression-fill materials’ or other more complex landforms (e.g. Fig. 8). Their width usually exceeds their length, thus forming broad features along footslopes. In most cases their total length is limited to a few kilometres. Their texture appears moderately rough when observed at the scales of HRSC (c. 15–20 m per pixel resolution) and MOC (c. 3–5 m per pixel resolution); where high-resolution MOC, CTX and HiRISE image data are available, their surface even appears blocky (Fig. 5d).

Protalus lobes tend to develop preferentially on south-facing slopes in the study area both in the case of linear south-facing scarps and inner rims of impact craters. The apparent flow direction is from north to south. The correlation between exposure and the development of protalus lobes is much greater than for any other landforms discussed here (Fig. 9).

Impact craters on these lobate landforms are scarce, with lower densities than any other feature described here. This is also consistent with the observed geometrical relationship between the different possible periglacial landforms in the study area, in that protalus lobes can be seen to be overlapping other landforms and demonstrate a young age.

The thickness of the protalus lobes can be evaluated using MOLA PEDR profiles; thicknesses range from a few tens of metres up to approximately 200 m (Fig. 6). Topographical profiling on these landforms has been performed using PEDR rather than HRSC DEM because of their relatively small size, and thus are not well resolved on stereo imagery but rather are detectable on single MOLA

Fig. 6. Topography of protalus lobes (MOLA, HRSC profiles, contours, etc.). (a) MOLA PEDR profile location, over the HRSC nadir image (orbit 292). (b) PEDR profile 15467, showing a convex profile of the protalus lobe. Zoomed inset shows the actual MOLA shot location. (c) MOLA PEDR profile location, over the HRSC nadir image (orbit 497). (d) PEDR profile 13002. Image credit: ESA/DLR/FUB.

Protalus lobes and ramparts

Protalus lobes (Shakesby 1997) are commonly found in the study area in close association with impact-crater rims and, in general, fault scarps resulting from compressional or extensional deformation. The lobes are characterized by multiple lobate concentric ridges with a relatively simple geometry when compared with the fill materials described in the subsection on ‘Lineated crater/depression-fill materials’ or other more complex landforms (e.g. Fig. 8). Their width usually exceeds their length, thus forming broad features along footslopes. In most cases their total length is limited to a few kilometres. Their texture appears moderately rough when observed at the scales of HRSC (c. 15–20 m per pixel resolution) and MOC (c. 3–5 m per pixel resolution); where high-resolution MOC, CTX and HiRISE image data are available, their surface even appears blocky (Fig. 5d).

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shots (Fig. 6). Moreover, they often occur on impact-crater rims and other types of scarps, producing strong shadows (Fig. 5b). The greatest convex parts of these rock-glacier-like landforms have slopes of up to about 7°.

**Association of landforms**

At some point, probably much later than for previous fluvial activity (Dohm *et al.* 2001b; Ansan & Mangold 2006), extensive ice-rich mantling (Figs 3e, 4 & 8) appears to have occurred in extensive areas within the mountain range of the Thaumasia Highlands. This possibly occurred over a specific time or, perhaps, as multiple episodes. This may or may not have coincided with a large glacial cover (Dohm *et al.* 2001a, b, 2007).

Our analysis shows distinct landform development through time in the Thaumasia Highlands region. A generic sequence of periglacial landform development in the study area includes (in chronological order) the following. (1) The poorly time constrained development of extensive lineated fill materials (Fig. 3a–c) (areas of c. 150–170 km²), which presently exhibit possible thermokarst (Fig. 3a) and/or sublimation features together with possible impact craters; these landforms may be remnants of more extensive ice sheets and/or glaciers (Dickson *et al.* 2006, 2008). (2) Emplacement of moderately sized debris aprons (areas of several tens of kilometres), which appear to be ‘deflated’. (3) The formation of isolated small protalus lobes (Fig. 10) marked by a few, if any, impact craters visible at available image resolutions (lengths of c. 2–5 km); protalus ramparts, which are several hundreds of metres to a few kilometres in extent, are also to be linked to this phase (Fig. 5). (4) Progressive sublimation and the deflation of landforms, possibly occurring under obliquity conditions similar to the present, leading to the currently observed association of landforms (Fig. 10). This sequence of events would be in general agreement with the notion of Dickson & Head (2009), who suggested that current morphologies in mid-latitude...
craters reflect a late-stage phase in the most recent ice age on Mars.

Inferred directions of movements for the various landforms are variable. Some of them are more clearly linked to topography (slope and aspect), probably related to the geological setting, while others (mostly the smaller features such as protalus lobes and ramparts) display a more direct link to local topography, aspect and exposure.

**Discussion**

Landforms in the ancient mountain range of the Thaumasia Highlands region are the result of a complex geological history, which includes magmatic, tectonic, erosional and aggradational processes (all of which may not be mutually exclusive), the latest of which is dominated by periglacial processes. Landforms such as lineated

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Fig. 8. Complex deformed possible multi-stage example of fill, with possibly exhumed craters within the deposit. (a) Local setting (HRSC nadir mosaic). (b) Detail of the complex convoluted, textured deposit. Small protalus ramparts are marked ‘PR’ in the figure. Parallel white arrows are pointing towards the edge of the complex deposit, which might be a degraded lobe: the edge marks the contact with the texture crater floor (CTX P08_004266_1377XI_42S092W). Image credit: ESA/DLR/FUB and NASA/JPL/MSSS.
fill materials, for example, may result from some form of climate-driven phenomena.

Landforms presented here are often spatially associated, co-occurring at close distances, but have developed over different time periods, often overlapping. Also, the size of these two main groups of landforms is very different: lineated fill materials are extensive, with areas as large as 100 km²; while protalus lobes usually cover areas no larger than 5–10 km².

No clear distinction between rock glaciers and debris-covered glaciers can be made, and the difference between the two landforms appears to be subtle.

Linear and curvilinear fill materials have been interpreted as being related to the flow of ice (Squyres & Carr 1986) or eolian erosion (Zimbelman et al. 1989). Here, we favour the former hypothesis, although it is also possible that eolian erosion played some important role in modifying the landforms over long timescales, depleting the deposits of fine-grained material in association with the loss of volatiles through sublimation.

Relative-age relationships among the periglacial-like landforms can be determined in individual basins (e.g. Figs 3e, f & 5c), but it is more difficult to have a complete picture over a more regional extent, including the exact relationship between lineated fill materials and mantling. It is possible that both mantling (perhaps more extensive than observed at present) and the development of lineated fill materials occurred contemporaneously, and that both decreased with time, so producing the present residual landforms.

Crater-size frequency analyses to derive absolute ages will produce unreliable absolute ages due to both the limited extents of the features and the flow deformation of the materials. The small extent of the discovered protalus lobes, for example, makes it difficult to estimate absolute formational ages. Geometrical and stratigraphic relationships indicate a more recent age for the relatively small protalus lobes with respect to lineated fill materials (e.g. Fig. 5a, c). A few of the features, such as the lineated valley-fill materials, are often marked by circular or quasi-circular depressions. We have not attempted to date their surfaces because it is difficult to determine whether the origin of the often-deformed features is impact (Figs 3 & 4). Their diameters are typically a few hundreds of metres.

Some of the lineated fill materials, most protalus lobes and the debris aprons appear to be inflated, suggestive of subsurface ice. While others appear to be more deflated morphologically (Figs 4c–f &

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**Fig. 9.** Inferred direction of the flow map of the protalus lobes (white) and crater/valley fill (black) inferred direction of movements. Protalus lobes appear more pristine, and mostly showing southward exposure and flow direction. Lineated crater fills show more deflated morphologies, and a wider distribution of flow directions. Image credit: ESA/ DLR/FUB.
6a, b), as observed in comparable deposits in different settings and locations on Mars (Dickson et al. 2008). The estimated amount of volume loss over a poorly constrained period of time can possibly be hinted at by the presence of terraces, ridges and moraine-like features (Dickson et al. 2008) at the edge of craters (Fig. 3b, c). The variation in thickness, based on these features, may be up to a few hundred metres (e.g. Dickson et al. 2008).

The presence of faults and their relationship with the emplacement, development and modification of lineated fill materials is also an issue; in Figure 3f a fault clearly deforms the textured floor and rim of an impact crater, but the extent of exhumation in such a setting is less clear. The fault could have a synsedimentary relationship with the fill materials of the impact crater or it could simply be that the infill materials partially infilled the fault and then was modified and later partially exhumed. We tend to favour pre/(syn?)-tectonic development of lineated fill materials as both the textured crater fills and the rim bedrock display fault scarps with a comparable morphological and degradational level (Fig. 3f).

The flow direction inferred from the lineated fill materials show little to no correlation with slope orientation, being more correlated with local and regional topography. However, mostly concave-upwards debris aprons and mostly convex-upwards protalus lobes have developed preferentially on south-facing slopes (pole facing), suggesting a stronger and temporarily closer role of morphoclimatic conditions during their development (Fig. 9). This is consistent with previous observations of glacial–periglacial features at mid- to low latitudes (e.g. Berman et al. 2005, 2009; Dickson et al. 2008; Hauber et al. 2008). Therefore, smaller lobes are linked to present morphoclimatic conditions and could still be active. Indeed, based on modelling, ice accumulation is possible in the Thaumasia Highlands region (Levrard et al. 2004; Forget et al. 2007) given that past obliquity conditions have been different to those of the present. Thus, the Thaumasia Highlands region may have retained a record of climatic events complementary to that which have been recorded in the northern hemisphere (e.g. Dickson et al. 2008; Hauber et al. 2008; van Gasselt et al. 2008).

Some of the areas show complex fill materials that have possibly been deformed by more than one sequence of events, either with a different direction of movement superimposed (e.g. Figs 3c, 5a & 8).
or with highly deformed fill materials – showing convoluted surface textures and the presence of possibly exhumed craters – being possibly linked to older or multiple different climatic periods. The evolution of the fill materials, which record multiple glacial–periglacial phases, is probably complex and may be difficult to unravel. However, it may prove useful to correlate and extend the observations over a wide range of locations on Mars (e.g. Dickson et al. 2008; Hauber et al. 2008; van Gasselt et al. 2008).

The location and development of the possible periglacial landforms may be strongly linked to the pre-existing topography because the ancient rugged mountain range of the Thaumasia Highlands region comprise impact craters of varying size and degradational states, extensional and contractional faults and folds, complex rift systems, and shield volcanoes that formed along the rift systems. All of these features would influence subsequent geological and geomorphological activities that include periglacial processes. Some of the lineated fill materials hosting impact craters appear to have been affected by fluvial erosion and deposition. In particular in the vicinity of Warrego Valles (Ansan & Mangold 2006), lobate deposits with lineated and convoluted textures occur in impact craters and other types of depressions that have been modified by fluvial activity, as evidenced by highly resurfaced channels which enter and/or exit the basins (Fig. 8). In fact, several of the more recent landforms, such as protalus lobes, appear to have a convex-upwards longitudinal profile, possibly suggesting (Clark et al. 1994) the active presence of an ice core.

In the Thaumasia Highlands region, the dominant concave-upwards profile of debris aprons, where present, is indicative of a past scenario involving the melting of ice cores of rock glaciers or debris-covered glaciers. In contrast, protalus lobes mostly show convex-upwards profiles (Fig. 6) that, together with their apparent relatively young age, is indicative of recent and/or current activity.

All landforms described here appear to be at moderately high altitude. Most of them are above 5000 m in altitude. Smaller ones, such as protalus lobes occurring on scarps with frequent shadows, are also found at elevations closer to 4000 m (Figs 2, 4d, f & 6b, d). Craters with sloping floors elsewhere in the southern hemisphere have also been described by Berman et al. (2005, 2009) at lower elevations. However, further observations on their latitudinal and altitudinal dependence across the hemisphere are still needed.

Although the nature and evolution of such landforms are often controversially discussed (e.g. Head et al. 2006; Hauber et al. 2008; van Gasselt et al. 2008), there is evidence that the existence and evolution of such landforms is related to climatic variations controlled by the orbital configuration of Mars (Levrard et al. 2004; Forget et al. 2007), which was responsible for the deposition of ice in the equatorial region during high-obliquity phases and the depletion of an ice reservoir during periods of low obliquities.

The search for subsurface ice or ice–rock mixture signatures with sounding radar data such as SHARAD (Shallow Radar on board MRO) has proved to be successful in the detection of ice in debris aprons in a few cases (Holt et al. 2008), but thus far unsuccessful in the Thaumasia Highlands region. This may be due either to the lack of subsurface ice-rich/ice-depleted interfaces or to the presence of a smooth gradient of ice content, which would not produce a sharp reflector in subsurface sounding radar data. Moreover, the small size of the landforms (apart from large craters with lineated fills), as well as the generally high surface roughness in the Thaumasia Highlands region, makes the analysis of subsurface radar data problematic.

**Conclusions and future prospects**

The Thaumasia Highlands region provides the geomorphological setting necessary for the formation of creep-related landforms caused by an abundance of high-relief slopes and a tectonically dissected terrain, which allows the accumulation and supply of wall-rock debris at footslopes.

In our survey, we identified flow and creep morphologies exhibiting a lobate to tongue-like shape, 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. Larger, stratigraphically older lineated fill materials may have recorded older, more enhanced glacial phases (Dickson et al. 2006, 2008). The general lack of impact craters suggests relatively young surface ages. Although water ice is not considered to be presently stable at equatorial latitudes, there are morphological indicators suggestive of the reactivation and/or formation of such landforms in the transitional belt between equatorial latitudes and mid-latitudes on Mars during geologically recent times (e.g. Levrard et al. 2004; Forget et al. 2006).

Radar-based analysis of the Thaumasia Highlands region using SHARAD, although difficult due to the attenuation of the radar signature caused by the rugged, highly modified mountain-forming rock materials, may, with the aid of high-resolution stereo-derived topography (e.g. Gwinner et al. 2005; Dumke et al. 2008) for radar topographic clutter modelling (e.g. Cutigli et al. 2007), help constrain the presence of ice in the landforms described in this work.
Being one of the few high-altitude regions on Mars located within the southern mid-latitudes, the ancient mountain range of the Thaumasia Highlands may be key to unfolding the geological and geomorphological record of past climatic phases on Mars.

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References


