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Geomorphological characterisation and interpretation of a mid-latitude glacier-like form: Hellas Planitia, Mars

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ABSTRACT

We describe and interpret the surface terrain types associated with a widely-reported ~4 km long, mid-latitude martian viscous flow feature (VFF). The feature is located in the southern hemisphere, on the poleward-facing rim of a ~60 km-diameter crater in eastern Hellas Planitia. High Resolution Imaging Science Experiment (HiRISE) images, analysed in both 2D and 3D, reveal that the upper margin of the feature is bounded by steep (~30°) headwalls, typically some tens of metres high, that are formed from unconsolidated material and characterised by a series of slope–parallel linear incisions. Below these incised headwalls, the feature flows at a general angle of ~10° from a broad upper basin to a confined lower tongue that is bounded by a nested sequence of elongate raised ridges. These characteristics are typical of several VFFs in the region and are strikingly similar to moraine-bounded valley glaciers on Earth, and we sub-classify this feature as a 'glacier-like form' (GLF)[1]. The GLF comprises five distinctive surface terrain types that contrast sharply with surface characteristics outside its bounding moraines. Four of these terrains (scaly terrain, polygonized terrain, linear terrain and mound-and-tail terrain) are located within the GLF's innermost bounding moraine, while the fifth (rectilinear-ridge terrain) is located between its frontal moraines. These terrains are mapped, characterised and associated with possible mechanisms of formation to draw inferences about the GLF's glaciology and glacial history. This analysis suggests that the GLF reached its maximal extent in the geologically-recent past, and that it may have been partially wet-based at that time. Subsequent to this phase, the GLF experienced an extended period of general recession that has been punctuated by several episodes of still-stand or advance. Currently, the GLF's basin appears to be composed of a lower zone that is dominated by an exposed former glacier bed and an upper zone that may still contain a now-degraded and dust-mantled viscous mass, similar to many partially-glacierized basins on Earth.

1. Introduction

Mars exhibits many landscape features that are similar to glacial ice masses and ice-moulded landscapes on Earth (e.g., Kargel and Strom, 1992). In addition to the polar ice caps, numerous ice-mass-like viscous flow features (VFFs) have been identified and characterised in the martian mid-latitudes (e.g., Hartmann et al., 2003; Head et al., 2003; Kargel, 2004; Mahaney et al., 2007; Marchant and Head, 2003; Milliken et al., 2003). These lobate VFFs generally contrast with mid-latitude permafrost debris-flows or landslides in that the latter are generally raised above the surrounding landscape and have notable headwall supply hollows (e.g., van Gasselt et al., 2007). Flow modelling and investigations of crater density indicate that many VFFs, including that investigated herein (e.g., Hartmann, 2005), are probably geologically recent, between ~10^5 and 10^7 years old.

One particular group of VFFs is visually similar in terms of their large-scale geometry and characteristics to valley glaciers on Earth, termed 'glacier like flows' (GLFs) by Arfstrom and Hartmann (2005). Most GLFs accordingly have a broad upper basin that merges gradually with the surrounding topography, and a tongue that is typically confined by raised bounding ridges. Investigations of their surface form also generally indicate that they are 'cold-based' or frozen to their substrate throughout (Head and Marchant,

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[1] This terminology contrasts slightly with Hartmann's original usage in that we refer to the feature as a 'form' rather than a 'flow'. This preference is based on several considerations, including that: (i) although inferred, flow has not yet been measured at such features, (ii) supplementary (basal) motion components cannot yet be ruled out, and (iii) the term 'flow' can refer to both a form and a process of ice-mass motion, which could lead to confusion.

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2003; Shean et al., 2005). However, recent evidence points to the possibility that martian glaciation may, at some period in the past, have been at least partially wet-based. For example, Arfstrom and Hartmann (2005) argued that the distinctive moraine-like ridges bounding several mid-latitude martian VFFs (including that investigated herein) could form by water-lubricated sediment squeezing from beneath the ice, implicitly requiring wet-based glacial conditions. In terms of earlier glaciations, Banks et al. (2009) interpreted the well-known (but undated) network of sinuous and anastomosing ridges in southern Argyre Planitia (~30–55°S) as subglacial eskers, requiring the presence of a large, wet-based ice mass. In an earlier study of the same area, Banks et al. (2008) had already reported the presence of elongate bedforms and large-scale grooves or striations in the rock surface and interpreted these erosional features in terms of wet-based glacial activity, probably of pre-Amazonian age. Many ice masses on Earth are, in fact, neither wholly cold-based nor wholly wet-based but a combination of both. Such *polythermal* ice masses generally have a warm-based interior (where the thick overlying ice provides sufficient insulation for the 0 °C isotherm to rise to intersect the ice-bed interface) and cold-based margins (where the ice is thinner and the 0 °C isotherm is located within the subglacial substrate) (e.g., Paterson, 1994). These countering influences of surface temperature and ice thickness, for example, allow significant regions of the base of the East Antarctic ice sheet to host large lakes (e.g., Siegert, 2000) and even its (significantly thinner) outlet glaciers to have portions of their interior beds that are wet-based (e.g., Hubbard et al., 2004; Robinson, 1984). Moreover, the thermal regime (i.e., temperate, cold, or polythermal) of any given terrestrial ice mass is likely to have changed through time in response to changes in surface temperature and ice thickness. Despite the hypothesised glacial origin attributed to martian GLFs, no study has yet investigated the detailed surface structure of a GLF with the aim of identifying mechanisms of formation, deformation and glacial history – particularly in the light of alternative thermal regimes.

One mid-latitude martian GLF in particular has attracted widespread attention as a type example of a martian glacier or rock glacier: that centred on 38.15°S and 113.16°E (Fig. 1). This feature is located inside the northern (i.e. pole-facing) rim of a 60–70 km diameter crater, centred on ~38.65°S; ~112.98°E, to the east of the Hellas basin. Initially, several investigators noted this feature's glacier-like outline and moraine-like bounding ridges (e.g., Hartmann et al., 2003; Kargel, 2004; Marchant and Head, 2003; Milliken et al., 2003). However, more detailed exploration of the feature's surface characteristics was limited by the (metres to tens of metres per pixel) resolution of the Mars Orbiter Camera images available at the time. Nonetheless, Arfstrom and Hartmann (2005) did note that the feature's lateral ridges appeared to be double-crested, indicating the possibility of separate glacial advances, while Marchant and Head (2003) observed the presence of 'chevron ridges' on the feature's inner surface, compatible with down-slope flow. Furthermore, both Arfstrom and Hartmann (2005) and Hartmann (2005) constrained the age of the feature's surface on the basis of the density-distribution of small (11–16 m diameter) impact craters, concluding that it was geologically recent (and not older than ~10 Ma), consistent with timescales from flow deformation studies (e.g., Milliken et al., 2003; Turtle et al., 2001).

The Mars Reconnaissance Orbiter's (MRO's) High Resolution Imaging Science Experiment (HiRISE) camera has captured this particular GLF in PSP_002320_1415 and PSP_3243_1415. Importantly, these images show (at a resolution of ~0.25 m per pixel) several terrain types that are similar to those associated with small-scale and relatively dynamic valley glaciers on Earth. The images therefore present an excellent opportunity to verify and expand on earlier interpretations of GLFs and to investigate this feature's glacial history on the basis of its structure and associated landforms.

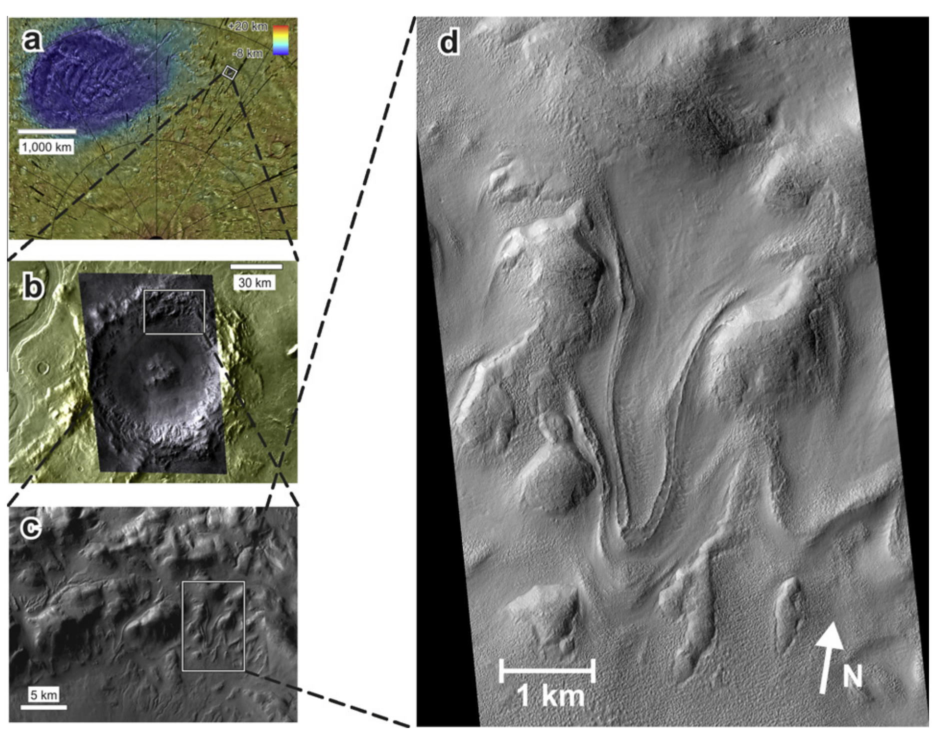

Fig. 1. Location and expansion of the glacier-like form (GLF) investigated herein. (a) Location of the host crater to the east of the Hellas basin illustrated as a MOLA elevation transparency superimposed on a Themis daytime IR mosaic. (b) View of the host crater illustrated as a Context (CTX) image mosaic overlaid on an expansion of (a). (c) Expanded CTX view of the inner northern rim of the host crater wall, illustrating the presence of at least nine GLFs in this vicinity. (d) The GLF investigated herein, illustrated as a section of HiRISE image PSP_002320_1415. The scene is illuminated from the west with the Sun ~23° above the horizon.

2. Methods

In this paper we identify, characterise and map the surface terrain types present on the GLF in PSP_002320_1415 and PSP_3243_1415. Initial terrain identification was carried out by eye and mapping was carried out using the software package ArcGIS. The recording of this GLF in two offset HiRISE images has also allowed us to generate a digital elevation model (DEM) of its surface, permitting characterisation and interpretation on the basis of local relief and slope as well as from planform visual assessment. The DEM was generated using the methods of Kirk et al. (2008). Radiometric calibration, corrections for detector orientation and optical distortions, and mosaicking were carried out using the USGS' Integrated Software for Images and Spectrometers Version 3.0 (Isis 3) software package. We subsequently carried out standard stereogrammetrical techniques using BAE Systems' SOCET SET. Control points distributed across the overlap of the two HiRISE images were used to solve for spacecraft orientation, yielding an RMS discrepancy of ~0.4 pixels (corresponding to a DEM horizontal accuracy of ~0.1 m). However, the minimum attainable horizontal resolution is three HiRISE pixels, so the DEM was gridded at 1 m per pixel. In the vertical, surface elevations were controlled using 202 Mars Orbiter Laser Altimeter (MOLA) data points (125 from individual points and 77 from gridded points). MOLA data have a vertical accuracy of 1 m (Smith et al., 2001), allowing a DEM precision of 0.2 m. Spacecraft jitter unresolved by orientation kernels resulted in slightly larger errors at CCD boundaries, and also in locations where the pixel-matching algorithm was unsuccessful. Such artefacts affected only very local portions of the DEM generated for this study, and were clearly distinguishable on the resulting shaded relief map – allowing their *ad hoc* removal. Thus, no smoothing was performed on any portion of the DEM presented in herein.

3. GLF description

3.1. Physical setting and feature-scale characteristics

The ~4 km long and ~1–2 km wide GLF illustrated in Figs. 1 and 2 is typical of numerous others located on the rim of this particular crater, as revealed by MRO's larger-scale Context Camera (CTX) images (e.g. Fig. 1c). Similar features have also been tentatively identified elsewhere in eastern Hellas (e.g. in CTX image P02_001964_1416_XI_38S247W). Farther afield, a planetary-scale inventory of several thousand CTX images has identified several populations of GLF-like features. These are overwhelmingly located in Mars' mid-latitudes (e.g., Baker et al., 2010). For example, the high-relief areas of Protonilus Mensae and Deuteronilus Mensae feature high numbers of GLFs, often found in association with, or feeding into, larger lobate debris aprons or lineated valley fill (e.g., Morgan et al., 2009). However, as noted earlier by Marchant and Head (2003), these populations tend to cluster into local concentrations, similar to those illustrated in Fig. 1c, implying that correspondingly specific local or regional conditions are required for GLF formation (e.g., Forget et al., 2006) and/or preservation (e.g., Head et al., 2010). Thus, while these features all appear within the mid-latitude dissected mantle terrain (Milliken et al., 2003), which is generally characterised by periglacial surfaces and believed to contain near-surface water ice, they are by no means ubiquitous throughout this terrain type (e.g., Holt et al., 2008; Plaut et al., 2009).

Illustrations of the GLF investigated herein in planform (Fig. 1d) and draped onto its DEM (Fig. 2a) reveal that it extends downslope at a general angle of ~10° (Fig. 2b) from a broad upper basin to an elongate lower tongue that is enclosed by a sequence of up to four raised bounding ridges. Older and less distinct ridge remnants may additionally be present further from the feature's current basin. In Fig. 3, these ridges are marked onto a geomorphic overlay of the GLF, outlining its prominent features and surface terrains. Interrogation of the DEM indicates that relative relief between the moraines and the GLF surface generally increases down-slope to ~20–30 m towards its terminus (e.g., Fig. 2c). The upper basin grades into the surrounding terrain with no indication of large-scale landscape hollows from which mass could have been eroded by mass-movement processes to supply the lower basin (Fig. 2a). Further, and as reported by Marchant and Head (2003), the surface of the central region of the GLF is characterised by the presence of subdued chevron-type ridges (Fig. 2a), consistent with more rapid surface motion along the GLF's centreline than towards its lateral edges.

Within the innermost bounding moraine, the GLF's surface (Fig. 1d) is of a generally uniform reflectance, similar to the martian surface outside the ridges, indicating ubiquitous debris cover. The inner surface also shows little evidence of wind deflation and/or degradation and is devoid of large impact craters, consistent with larger VFFs identified elsewhere on Mars and calculated to have formed within the last ~0.4 Myr (Head et al., 2003).

3.2. Surface terrain types

The resolution of the HiRISE images has allowed a new assemblage of GLF surface terrain types to be identified and investigated. These terrains contrast markedly with the surface types that predominate outside the immediate vicinity of the GLF. These 'extra-GLF' terrains are dominated by two forms: (i) dust-mantled rocky uplands (Fig. 4a) and (ii) more subdued hilly lowlands (Fig. 4b). Within the GLF's bounding moraines, terrain types change progressively from the feature's headwall to its terminus – commonly grading into each other over distances of some tens to hundreds of metres. We have identified and mapped the distribution of the predominant terrains over the complete surface of the GLF (illustrated in Fig. 3 and summarised in Table 1). Below, we describe these surface terrains sequentially from the head of the GLF to its terminus.

3.2.1. Incised-headwall terrain

Although outside the GLF proper, the feature's upper basin is bounded by a steep (~30°) ribbon of material that is typically some tens of metres wide and covers the equivalent of ~3% of the area of the GLF (Table 1). The headwall is distinctively dissected by multiple, sub-parallel linear troughs that are typically a few metres wide (Fig. 5a) and in all cases aligned parallel to the local slope – even where that local slope changes over some tens of metres. This intensely incised terrain is distinctive from all others identified in the image, including the rocky uplands above it and the surface of the GLF proper below it (Fig. 5a).

3.2.2. Scaly terrain

The uppermost ~36% (Table 1; Fig. 3) of the GLF's basin is composed of tessellating 'scales' that are typically five or six sided and 10–20 m across at their widest point (Fig. 6). Each scale has between one and three raised upslope-facing edges and a body that dips down-slope, resulting in sharply-incised scarps or cracks between adjacent scales. The terrain is gently concave upwards such that its surface slope decreases from $\geqslant 16°$ at the top of its extent to ~12° at its lower margin.

Near the headwalls of the GLF, this scaly terrain is scattered with rounded boulders of lateral dimension $\leqslant\sim 10$ m, the spatial density of which decreases rapidly over a distance of some tens of metres away from the headwall (Fig. 7a). Many of the largest of these

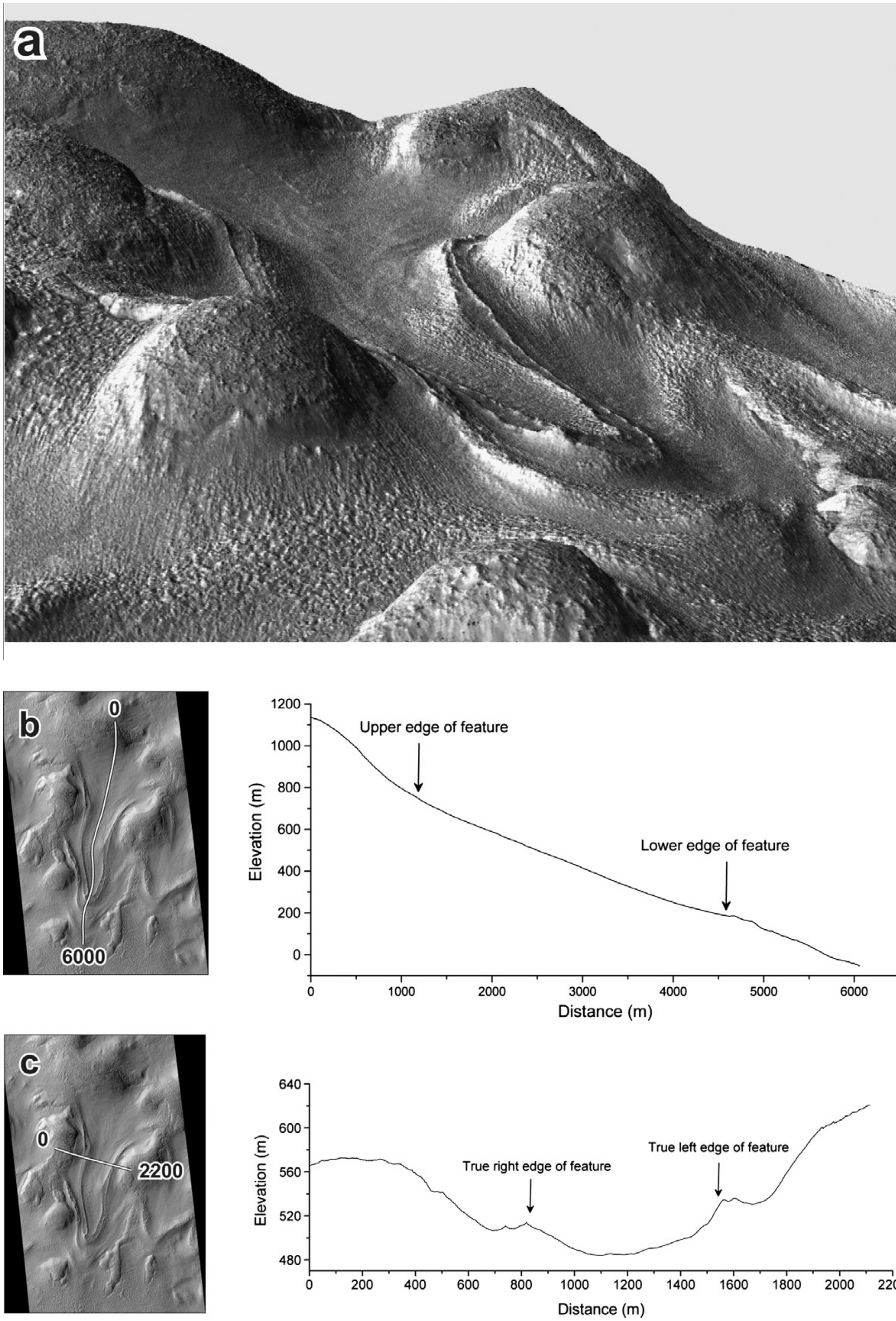

Fig. 2. Three-dimensional representation of the GLF investigated in this study. (a) HiRISE image from Fig. 1d draped over its (6× vertically-exaggerated) surface DEM. (b) Longitudinal profile along the centreline of the GLF. (c) Transverse profile across the GLF. The thumbnails indicate the locations of the transects in Fig. 1d.

boulders are also associated with incised trails that extend upslope from them and which generally narrow to match the width of their associated boulder at the point of contact (Fig. 7b). Trails also become less distinct with distance from the base of the headwall

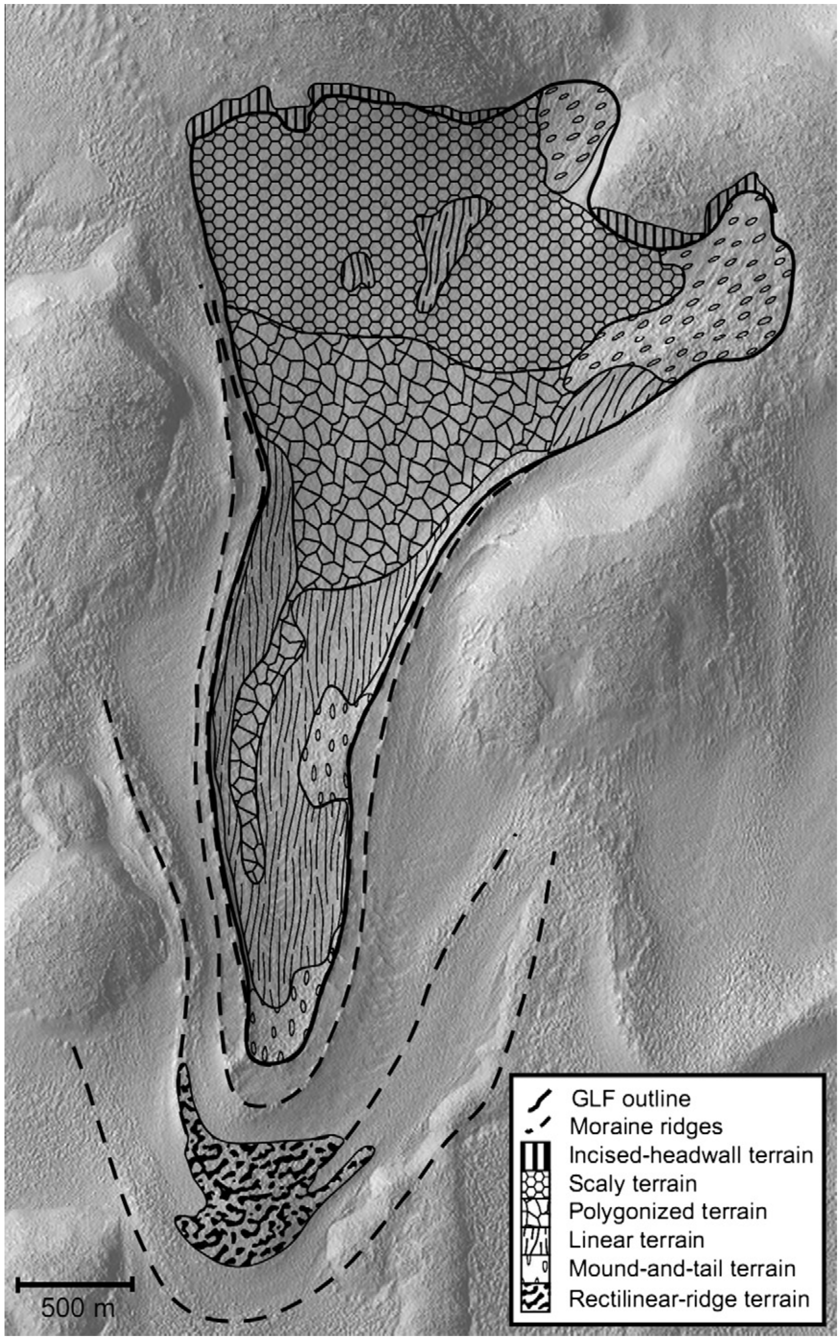

Fig. 3. Geomorphic map of the predominant surface features and terrains overlaid on the HiRISE image from Fig. 1d. Although illustrated here as sharp boundaries, the GLF's surface terrains typically grade into each other over distances of some tens to hundreds of metres.

slope such that there is no evidence of any trails at all beyond ~150 m, despite the presence of several large boulders here.

3.2.3. Polygonized terrain

Progressing down-GLF the scaly terrain merges over a few hundred metres into a terrain of tessellating polygons, each typically 5–10 m across (Fig. 8). This polygonized terrain has a uniform surface slope of ~10° and occupies ~25% of the GLF's surface area (Table 1; Fig. 3), covering much of the lower half of the upper basin and additionally extending as a thin central filament for a further ~1.5 km down-feature. In stark contrast to patterned ground identified elsewhere on Mars, the boundaries of many of this GLF's polygons, particularly further down-feature, are defined by uniformly ⩽~1 m-wide cracks or troughs (Fig. 9a) that are aligned sub-parallel to the local slope (Fig. 9b).

3.2.4. Linear terrain

In the lower half of the GLF, the polygonized terrain gradually merges into a more elongate surface texture (Fig. 10) that accounts for ~22% of the GLF's surface area (Table 1; Fig. 3). The ridges are aligned parallel to the elongation of the GLF, notably bending from NNE–SSW to N–S along the central region of the GLF's tongue (Fig. 11). The ridges are typically some decimetres high (Fig. 10b) and appear to be formed constructively rather than by erosion of the intervening troughs, although some of the surface incisions identified in the polygonized terrain continue for some hundreds

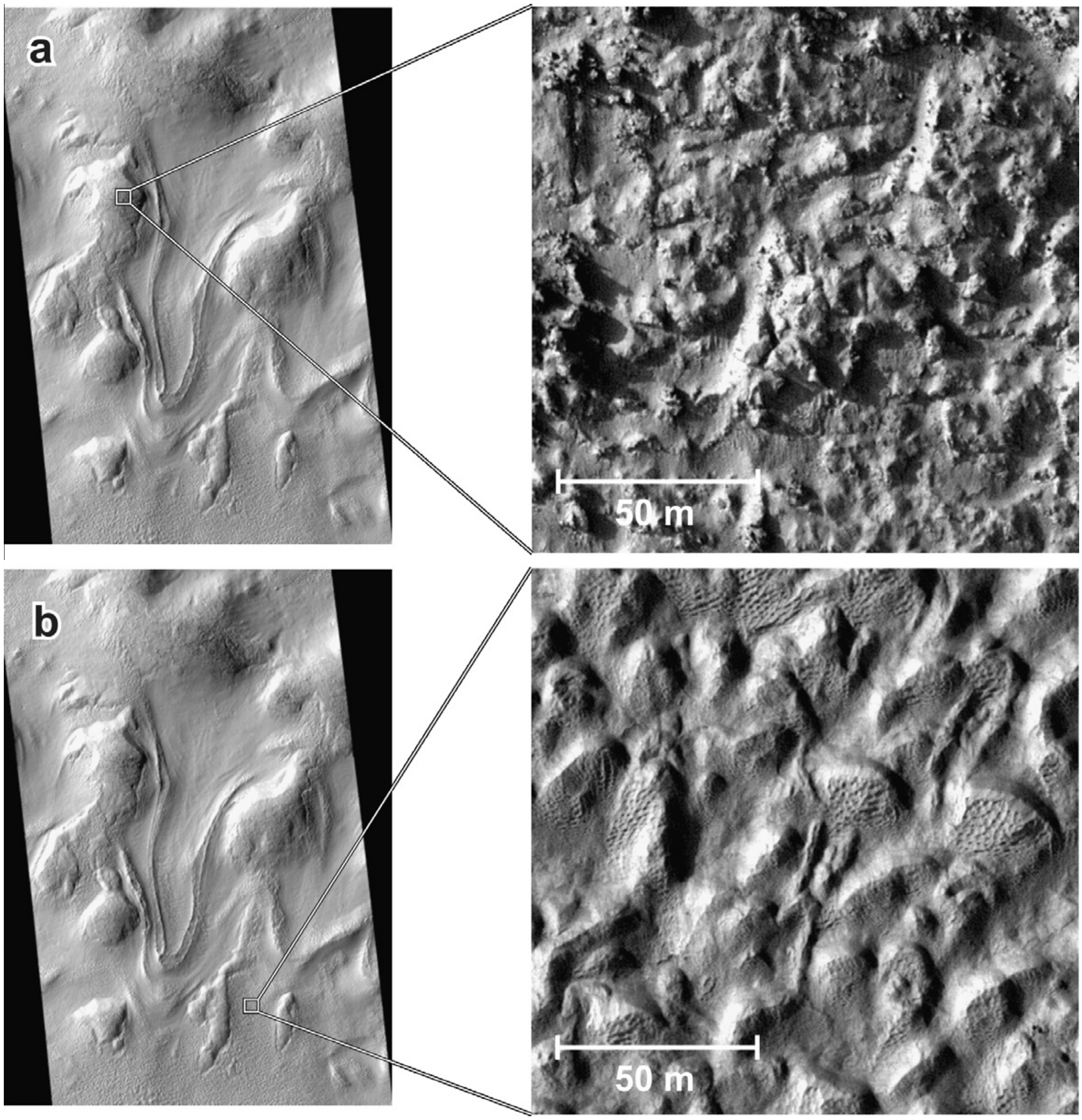

Fig. 4. Typical surface terrain types found outside the GLF investigated in this study. (a) Dust-mantled rocky uplands. (b) Subdued hilly lowlands. Neither of these terrain types is found within the bounding ridges of the GLF under investigation. Note that the ribbon-like feature extending N–S down the centre of (b) is similar to a terrestrial esker, but its interpretation lies outside of the scope of the present investigation. The thumbnails indicate the locations of the expansions in Fig. 1d.

of metres along these troughs. In a few conspicuous cases these channels also cut across the elongate ridges. The width and transverse spacing of the ridges remains constant, at ~5–15 m, throughout this zone. However, the length of individual ridges generally increases, from ~250 m mid-GLF to ~1 km approaching the terminus, yielding elongation ratios (length/width) of ~10–15 and ~100 respectively. Throughout this zone the orientation of the lineations is locally very consistent, being within ~2° of each other, even around the large-scale bend in the GLF. Much of the linear terrain, particularly in up-GLF locations, also exhibits surface cracking although not as strongly as within the polygonized terrain.

3.2.5. Mound-and-tail terrain

The lineations widen and become less distinct as they approach the GLF's terminus, until they break up into a terrain of closely-spaced and elongate mounds, each typically 30–50 m long, 10–30 m across, and 2–4 m high (Fig. 12). These features have a steep upglacier-facing core and a shallow elongate tail. The Hellas Planitia mounds are also geometrically continuous with the lineations that merge into them (Fig. 11), requiring an associated origin. In addition to its occurrence near the GLF's terminus, notable patches of mound-and-tail terrain can also be found elsewhere in the GLF's basin (Fig. 3), in this case above the scaly terrain at the head of the feature and adjacent to the linear terrain along the inside of the GLF's bend. The surface slope of the mound-and-tail terrain is correspondingly variable, from ~8° near the terminus, to ~20° at the head of the GLF. In total, this terrain accounts for ~15% of the surface area of the GLF.

3.2.6. Rectilinear-ridge terrain

Outside the GLF proper, but within its outermost bounding terminal moraine ridge, the surface is composed of a series of ridges, typically of tens of metres across and 2–3 m high (Fig. 13a). These ridges are preferentially elongated in an arc aligned parallel to the GLF's former terminus, covering an area equivalent to ~7% of that of the GLF. Accounting for the general (~4°) dip of this terrain away

Table 1
Summary of the spatial extent and organisation of the surface terrain types characterising the Hellas Planitia GLF investigated in this study. Slopes are averages calculated parallel to the alignment of the GLF.

Feature/terrain type	Area		Slope (°)	Notes
	(km^2)	(%)[a]		
Complete GLF	4.69	100	10	Entire feature excluding incised-headwall terrain and rectilinear-ridge terrain
Scaly terrain	1.67	36	12–16	Present over most of the GLF's upper basin. The scaly terrain's lower boundary merges over ~500 m into the polygonized terrain
Polygonized terrain	1.16	25	10	Present down-GLF of the scaly terrain. The polygonized terrain's lower boundary extends as a thin tongue, and merges over ~500 m, into the linear terrain
Linear terrain	1.03	22	8–12	Predominantly present over most of the GLF's laterally-confined lower tongue. Lineations bend NNE–SSW to N–S, following the GLF's overall shape. Two patches of linear terrain are also present in the GLF's upper basin, bounded by scaly terrain. The lower boundary of the linear terrain merges over ~200 m into the mound-and-tail terrain
Mound-and-tail terrain	0.71	15	8–20	Predominantly present within ~500 m of the terminus of the GLF. Individual forms are aligned parallel to the lineations that merge into them. This area of mound-and-tail terrain terminates abruptly at the innermost bounding latero-terminal moraine. Three less distinctive areas of mound-and-tail terrain are present elsewhere in the basin: one on the true left flank of the GLF's tongue and the other two in the uppermost NE corner of the GLF's basin. These exposures include a range of slopes, depending on location
Incised-headwall terrain	0.14	(3)	30	Present as a narrow ribbon along the headwall of the GLF. The terrain is formed from unconsolidated material that is incised by numerous slope–parallel troughs that terminate abruptly upon intersecting the scaly terrain of the GLF proper
Rectilinear-ridge terrain	0.31	(7)	4	Present inside the outermost arcuate terminal moraine ridge in the forefield of the GLF. The terrain's boundaries merge over some tens of metres into the surrounding extraglacial lowland terrain

[a] Expressed as a percentage of the area of the complete GLF. Percentages in brackets relate to terrain types located outside the GLF proper.

from the GLF, individual ridges are characterised by steep (~12–15°), rectilinear proximal slopes and shallower (~4–8°) and less uniform distal slopes (Fig. 13b).

4. GLF interpretation

4.1. Physical setting and feature-scale characteristics

The GLF's basin-scale characteristics strongly indicate that the feature is the close martian equivalent of a valley glacier, currently either active or relict, comprising an open upland accumulation basin feeding mass to an enclosed lowland tongue. The absence of a notable supply hollow above the basin suggests that the original mass that formed the GLF was largely supplied from the atmosphere or from within the surrounding ground. The latter interpretation is consistent with the geologically-recent release of ice or water from the near-surface of the dissected mantle terrain. Further, the chevron-type ridges present in the middle of the GLF (Fig. 2a) indicate laterally-compressive ductile flow in this zone where its two contributing basins merge. However, in the absence of local mass-balance information it cannot be stated whether mass has been preferentially lost from the lower basin (as is generally the case on Earth), or whether mass has been lost from the entirety of the feature following an earlier phase of accumulation. Figs. 1–3 reveal that at least two of the GLF's bounding ridges extend for >2 km up its lateral margins, strongly indicating that they are not folds or faults associated with tectonic compression. Visually-similar assemblages of bounding latero-terminal moraine ridges are common around debris-transporting glaciers that have recently receded on Earth (e.g., Glasser and Hambrey, 2002; Kruger, 1993). Specifically, each such moraine on Earth indicates the position of either a temporary glacier readvance or a still-stand during a prolonged period of more general recession, reflecting changes in mass balance driven by a corresponding variability in local temperature and/or accumulation (Benn and Evans, 2010). However, about one in 20 glaciers on Earth can advance and retreat periodically (and independently of climatic changes) as a response to internal instabilities that manifest themselves as surge-type behaviour (e.g., Raymond, 1987). The Hellas Planitia GLF shows none of the geomorphic characteristics associated with (terrestrial) surge-type glaciers (e.g., Sharp, 1988), and we do not therefore interpret it as such.

These terrestrial comparisons and mass-balance inferences support and strengthen the conclusions of previous researchers in attributing a fundamentally glacial origin to this feature. We therefore believe that this particular feature can justifiably be referred to as a 'glacier-like form' (GLF), even though it may now be partly or wholly relict and have more in common with a terrestrial rock glacier than a terrestrial (ice-dominated) glacier.

4.2. Surface terrain types

Below, we interpret the GLF's surface terrains, progressing sequentially down-GLF from its head to its terminus.

4.2.1. Incised-headwall terrain

The tens of metres wide ribbon of unconsolidated material bounding the upper margins of the GLF is very similar to ice-marginal moraines on Earth (Fig. 5c), interpreted to have been deposited during progressive recession since the time of maximum recent glacial extent (generally the Little Ice Age; Grove, 1988). This origin is also supported by the relatively sharp boundary between the incised-headwall terrain and the higher-elevation rocky upland terrain (Fig. 5a).

The apparently fresh, slope–parallel troughs in the incised-headwall terrain could result from one or more of several sets of processes, including mass movement (rock-fall), aeolian erosion and fluvial erosion. Formation by dry rock-fall alone is considered unlikely on account of the scale and sharpness of the incisions. The regular spacing of the incisions also suggests that fluid erosion exerts a primary control over their formation. Considering erosion by air and liquid water as the only realistic alternatives, two factors suggest that the latter predominates. First, unconsolidated lateral moraines formed since the Little Ice Age on Earth are commonly scored by similar partially or wholly fluvially-eroded gullies (Fig. 5c). These terrestrial gullies have a similar spacing to the incisions we report on the martian GLF and they are similarly short and straight. Second, the GLF's headwall incisions appear in all instances to run perpendicular to the local slope – changing with slope along the upper boundary of the GLF. While it is clear that water would be expected to behave in this manner it is by no means likely that wind direction could change so consistently at such a local scale. Thus, while we cannot be sure that these incisions are fluvial in origin (and the processes operating to maintain

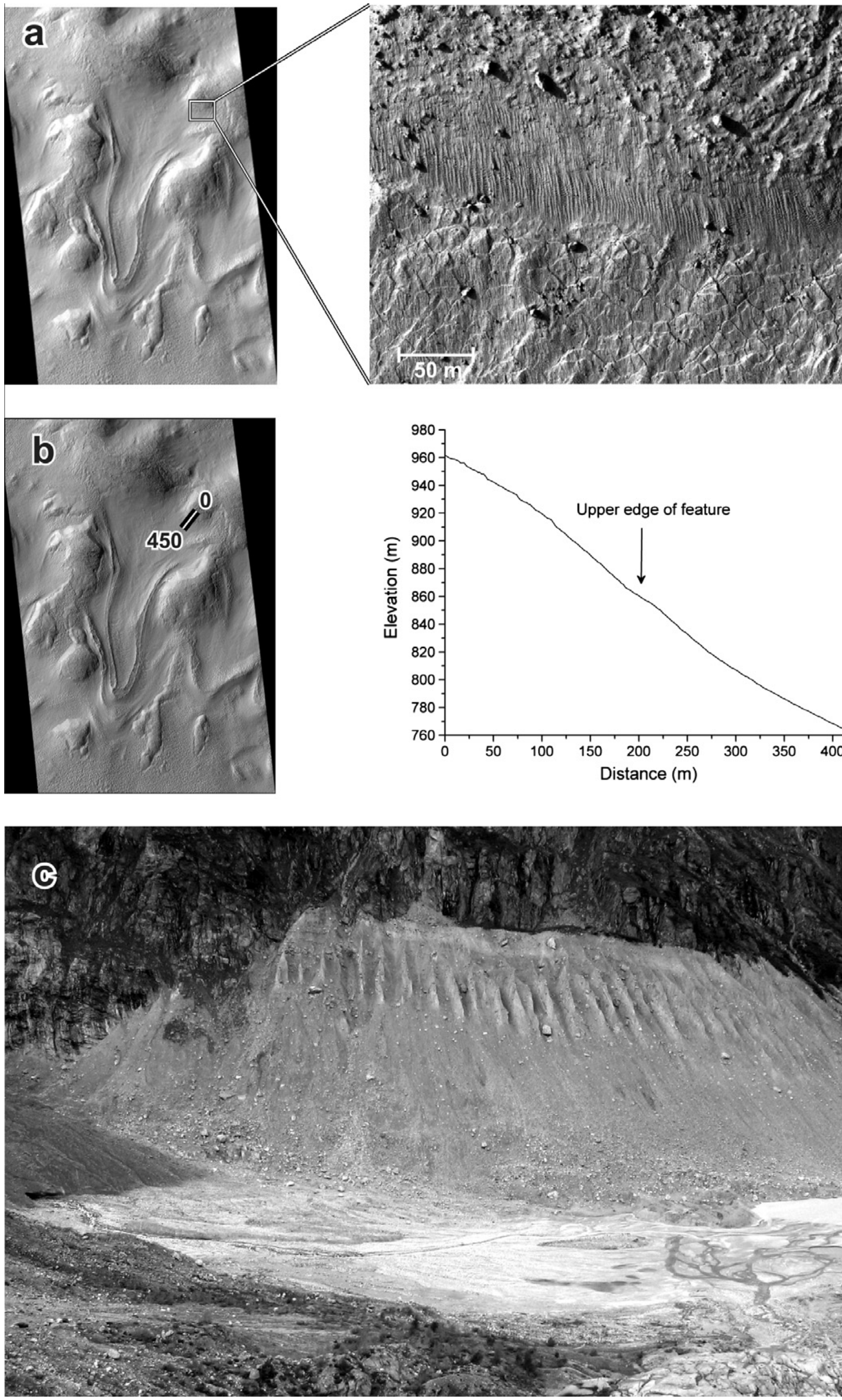

Fig. 5. Incised-headwall terrain. (a) Expanded HiRISE image of slope–parallel incisions located on the headwall of the martian GLF investigated in this study. (b) Longitudinal profile extending from the rocky upland, through the incised-headwall terrain and onto the head of the GLF. The thumbnails indicate the locations of the expansion and surface profile in Fig. 1d. (c) Oblique photograph of fluvial gullies incised into a remnant terrestrial lateral moraine (middle foreground), Glacier de Ferpècle, Switzerland. The current glacier terminus is visible in the middle left side of the image. The gullied moraine is ∼50 m high and individual gullies are straight and typically some metres across, similar in form and scale to the incisions in (a). Photograph by Bryn Hubbard.

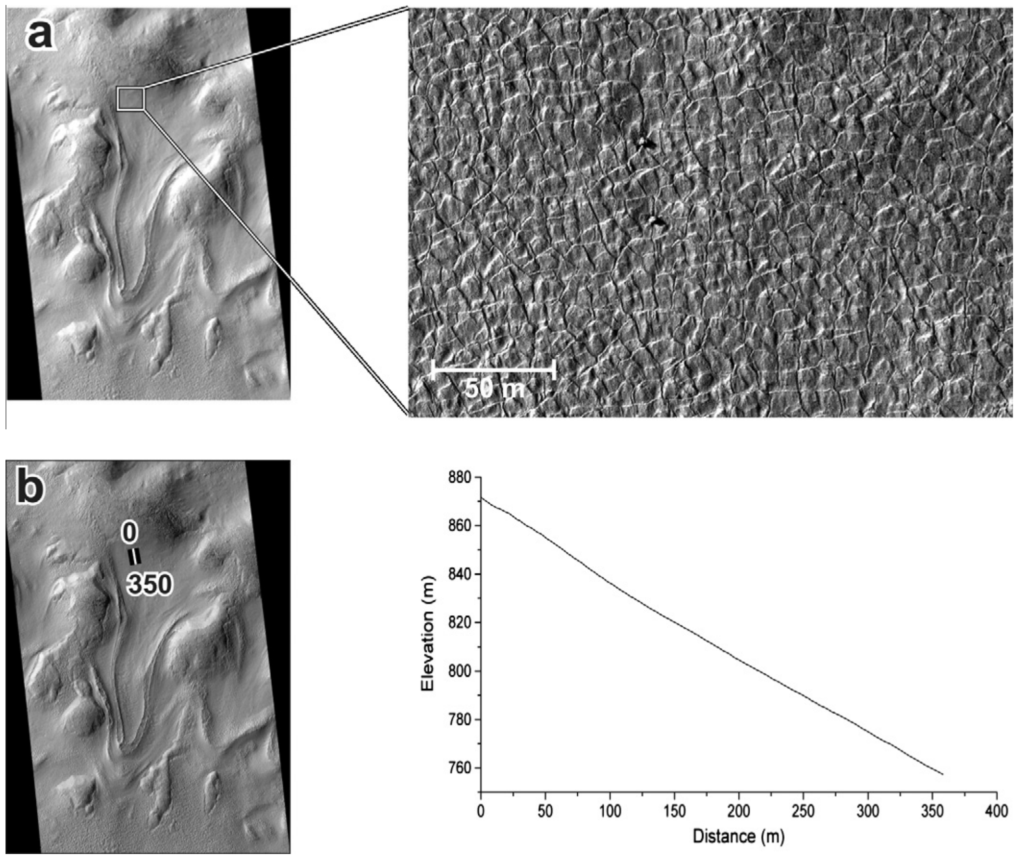

Fig. 6. Scaly terrain. (a) Expanded HiRISE image illustrating scaly terrain located in the uppermost reaches of the martian GLF investigated in this study. Note the presence of two boulders in the centre of the image. (b) Longitudinal profile along a region of scaly terrain. The thumbnails indicate the locations of the expansion and surface profile in Fig. 1d.

them are almost certainly not *exclusively* fluvial), we believe our evidence is more consistent with a fluvial origin than with a solely mass movement or aeolian one.

The well-preserved state of the troughs that characterise the incised-headwall terrain suggests that they were formed in the recent past. Assuming a fluvial origin for these incisions (above), it is quite possible that a geologically-recent source for such water could be near-surface ice (Costard et al., 2002) or surface snow (Christensen, 2006; Clow, 1987). This interpretation is consistent with that made for similar, but generally larger scale, features identified on Mars by, for example, Milliken et al. (2003) and Arfstrom and Hartmann (2005) who associated geologically recent (within the past few million years) gullying with VFFs. More recently, Dickson and Head (2009) presented a broad review of martian gullies and similarly concluded that many of the freshest forms are incised by meltwater generated from near-surface ice emplaced during the most recent high-obliquity cycles. Although these authors could not place an upper age on active gullying, they conclude from gully morphology and the age of gullied materials (e.g., Schon et al., 2009) that the process has probably occurred during the last ~1.25 Myr. Earlier, Malin et al. (2006) tentatively identified gullying within the past decade on the basis of repeat images of two small crater-wall channels (in Terra Sirenium and Centauri Montes), although in neither case could the erosional process involved be definitively identified as fluvial.

4.2.2. Scaly terrain

These cuesta-like shapes are generally similar to thermally cracked periglacial surfaces found on Earth and elsewhere on Mars, although smaller than martian examples hitherto reported (on the basis of generally coarser imagery) (e.g., Mangold, 2005; Mellon, 1997; Mellon et al., 2008). The longitudinal asymmetry in the surface slope of the scales on the Hellas Planitia GLF possibly reflects the additional influence of the ductile deformation of the underlying material in a down-slope direction. If the underlying material were ductile then deformation is most likely in this region of the GLF since the surface slope is steepest here (~12–16°). Like the headwall incisions, this scaly terrain is fresh in appearance, similarly indicating geologically recent (or current) formation or modification.

The roundness, location and spatial density of boulders located on the surface of the scaly terrain indicate that they have rolled off the headwall slope and come to a halt on the lower-angled surface of the GLF proper. Accepting this explanation, the location, orientation and width of the troughs extending up-GLF from the boulders indicate that the rolling motion of larger boulders is able to incise the surface of the scaly terrain to a depth of a few decimetres. We therefore infer that the surface of the scaly terrain is formed of unconsolidated material to a depth of some decimetres, and that it is probably consolidated, and possibly ductile, below this.

4.2.3. Polygonized terrain

The polygonized terrain is similar to periglacial patterned ground identified on both Earth and elsewhere within the dissected mantle terrain on Mars (e.g., Mangold, 2005). This terrain therefore probably represents a lower-angle (~10°) equivalent of the scaly terrain, both being formed by periglacial processes, including frost heave and contraction cracking (French, 2007).

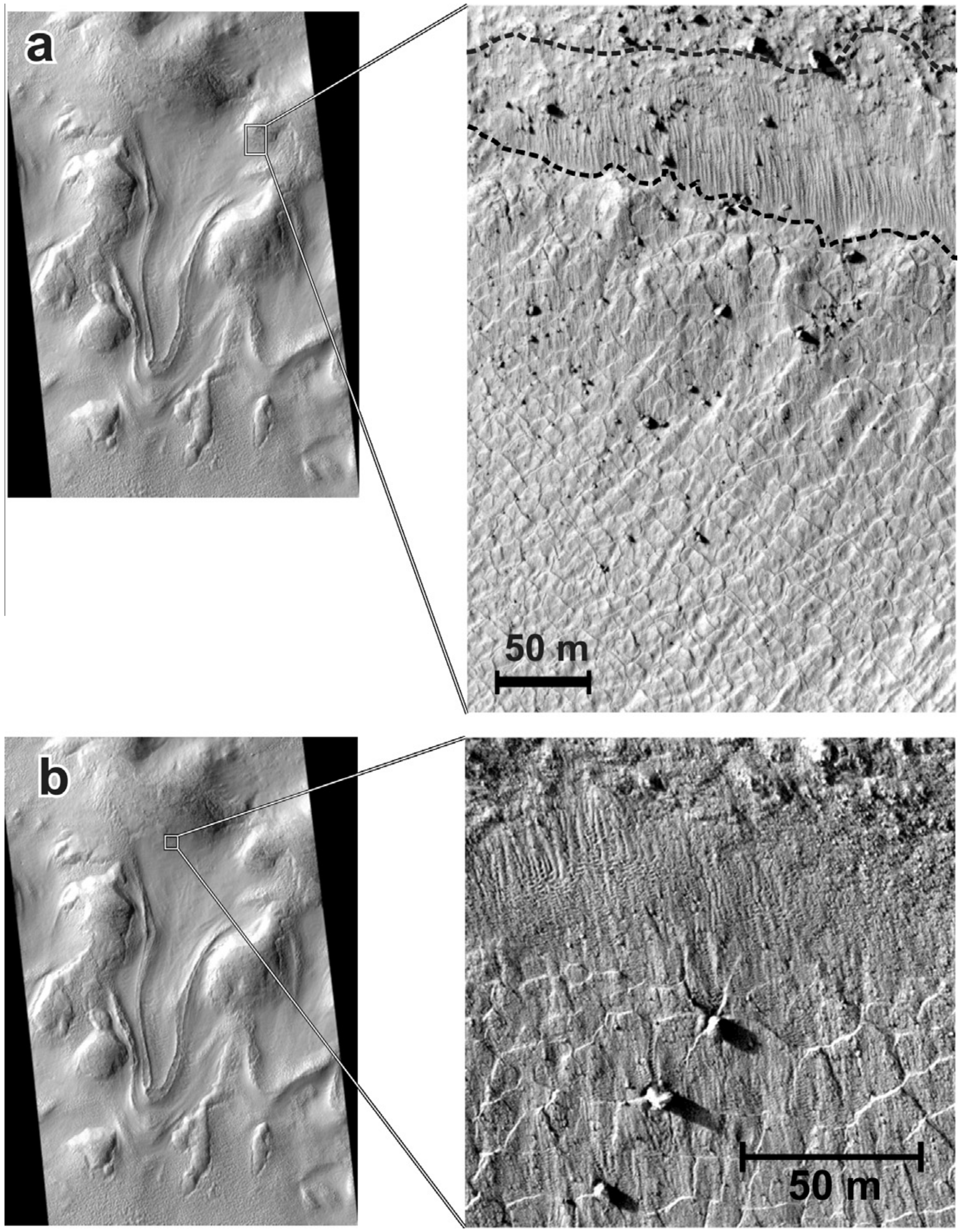

Fig. 7. Expanded HiRISE images of boulders at and below the contact between the incised-headwall terrain and the scaly terrain of the martian GLF investigated in this study. (a) Overview of surface boulders and the three terrains (demarcated by superimposed dashed lines: rocky uplands [top], incised-headwall terrain [centre-top], and scaly terrain [bottom]). Note the decrease in the spatial density of boulders down-GLF of the contact between the incised-headwall terrain and the scaly terrain. (b) Detail illustrating the presence of wide and shallow incised trails extending upslope of boulders lodged in the scaly terrain. The thumbnails indicate the locations of the expansions in Fig. 1d.

While the (approximately) radially-symmetrical cracking that characterises the scaly terrain and the polygonized terrain can be readily explained by periglacial processes, the joining up of these cracks to form extended, slope–parallel segments is more challenging to explain. These distinctive segments do not appear to have a direct analogue either on Earth or elsewhere on Mars. However, Levy et al. (2009) recently compared several instances of freshly-gullied polygonized terrain on Mars with terrestrial analogues from the Antarctic Dry Valleys. These authors concluded that, on Earth, such gullies appear to form from the 'top down' melting of residual snow deposited in incipient cracks and proto-gullies. In the absence of evidence to the contrary, the authors extended this model to the martian features. It is tempting to draw a similar conclusion for the extended incisions we observe in the polygonized terrain on the GLF investigated herein. However, any explanation would also need to account for the relatively short reach of individual incised segments, the absence of a coherent network of segments and the lateral passage of incisions across raised lineations. Such an investigation would require detailed study of these features, possibly including a range of GLFs, and lies beyond the scope of this paper.

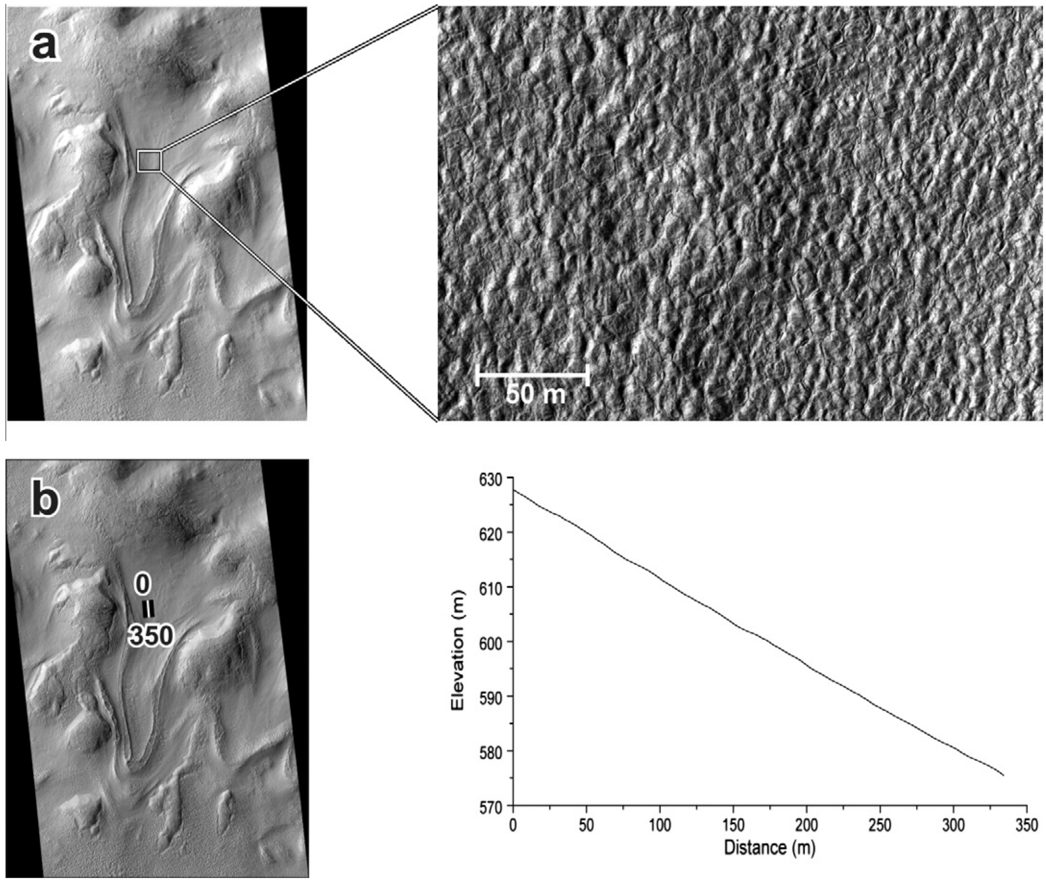

Fig. 8. Polygonized terrain. (a) Expanded HiRISE image illustrating polygonized terrain located in the upper and middle reaches of the martian GLF investigated in this study. (b) Longitudinal profile along a region of polygonized terrain. The thumbnails indicate the locations of the expansion and surface profile in Fig. 1d.

4.2.4. Linear terrain

The linear terrain appears to be broadly similar to three glacier-related features on Earth: (a) supraglacial medial moraines (formed from debris derived from upglacier point sources, or the coalescence of common lateral moraines where tributaries feed into compound glacier basins); (b) supraglacial longitudinal foliation (formed by the differential erosion of layers of ice of differing crystallographic and included bubble compositions); and (c) elongate subglacial bedforms (formed as a result of the interaction of the base of a glacier with its underlying sedimentary substrate). Since the Hellas Planitia GLF basin is geometrically simple with no notable point sources, and the lineations extend across the full width of the feature, these lineations are not interpreted as supraglacial medial moraines. Further, Figs. 10 and 11 reveal three geometrical characteristics of these lineations that mitigate against formation as supraglacial longitudinal ice foliation. First, where an individual lineation terminates upglacier of another, the two are commonly offset laterally. This contrasts with supraglacial longitudinal foliation, which is characterised by a high degree of longitudinal coherence, reflecting their deformation-related evolution. Second, the Hellas Planitia lineations are both wider and more widely-spaced than terrestrial equivalents (both typically decimetres to metres). Third, the lineations on the Hellas Planitia GLF pinch-out towards the terminus, in contrast to terrestrial longitudinal foliation which persists, or is enhanced, longitudinally. We therefore interpret these lineations not as supraglacial features but as elongate subglacial bedforms. Their large scale and absence of boulders marking their up-flow end indicates that they are not flutes. Instead, their spatial coherence, morphometry and fidelity to the flow direction of the GLF (including bending with it along the tongue) indicate that these features are most closely related to (although they are typically shorter than) glacial *megalineations* on Earth (e.g., Clark and Stokes, 2001). Terrestrial megalineations are generally related to fast ice flow which is, in turn, explained by ice-bed lubrication in the presence of basal meltwater (Clark, 1994).

Thus, while we cannot be sure that the lineations on the Hellas Planitia GLF are the small-scale martian equivalent of terrestrial megalineations, they appear to be more similar to these than to alternative terrestrial analogues. If these lineations are martian subglacial bedforms then this strongly implies water-lubricated ice flow at the time of their formation, which (since they extend right to the base of the GLF's lateral moraines) was probably at the GLF's maximum recent extent.

4.2.5. Mound-and-tail terrain

As far as we are aware there is no direct martian or Earth equivalent to the mound-and-tail terrain (Fig. 12). The closest terrestrial equivalents are drumlins, but the scale of the mounds on the Hellas Planitia GLF is several times smaller than that of typical drumlins on Earth. In an analysis of approaching 60,000 terrestrial drumlins, Clark et al. (2009) identified a modal length of 393–441 m and a modal width 173–183 m, while the GLF's mound-and-tail features are typically an order of magnitude smaller than this. Nevertheless, both terrestrial drumlins and the mounds on the surface of the Hellas Planitia GLF have similar shapes, with elongation ratios typically in the range 2.0–2.3. It is also worth noting that the smallest drumlins identified by Clark et al. (2009) were limited by the 5 m spatial resolution of their analysis.

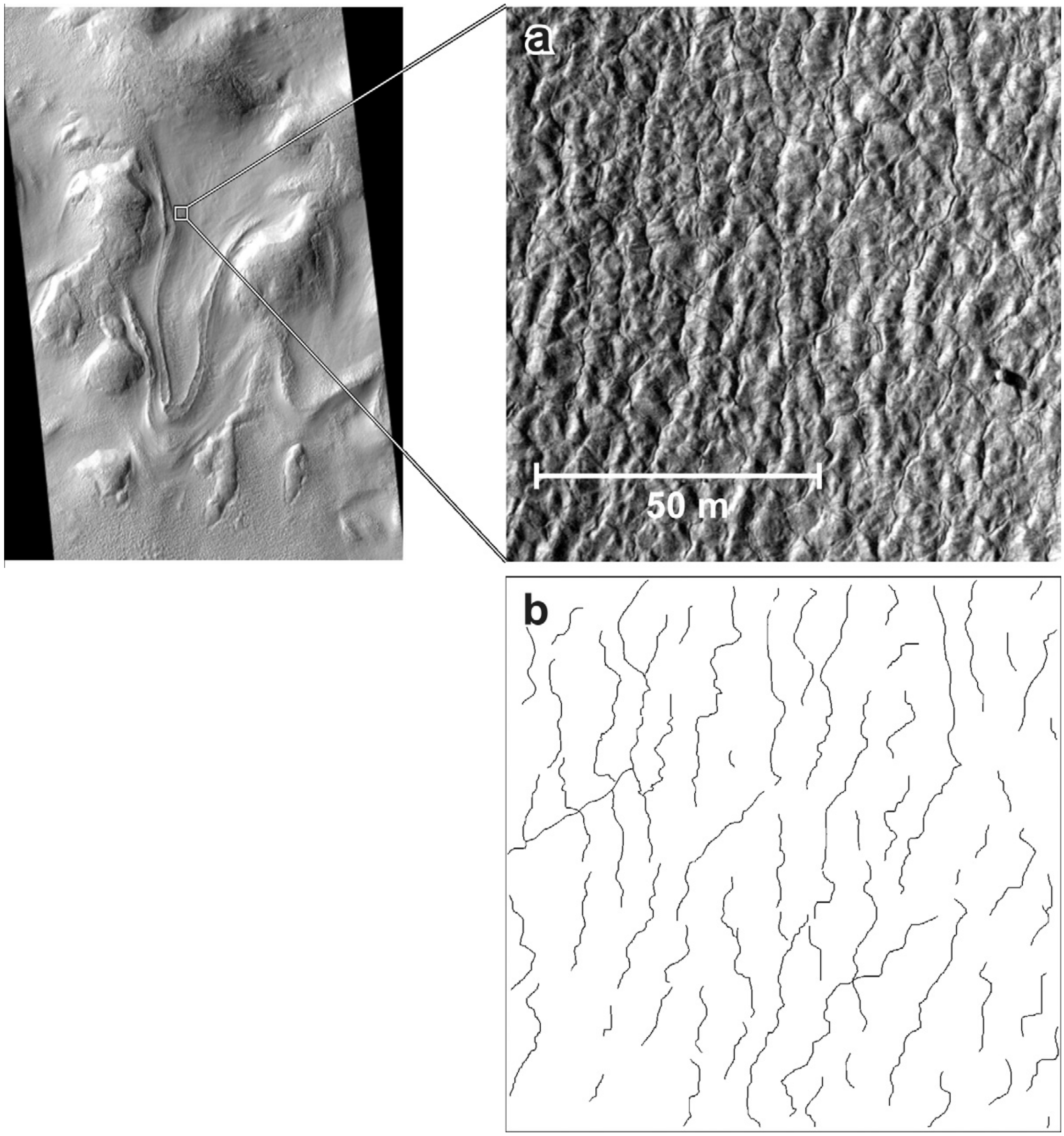

Fig. 9. Extended surface incisions. (a) Expanded HiRISE image illustrating approximately slope–parallel incisions at the boundaries of individual polygons within the polygonized terrain located on the martian GLF investigated in this study. The thumbnail indicates the location of the expansion in Fig. 1d. (b) Trace of the surface incisions illustrated in (a).

It is also important to consider that the GLF's mound-and-tail terrain is geometrically and morphologically continuous with the lineations that merge into them (Fig. 11), requiring an associated origin. Thus, although tentative, the most likely origin consistent with the evidence presented above is that both the lineations and the mound-and-tail forms are streamlined glacial bedforms – the former approximating megalineations and the latter drumlins (but both at a smaller scale than is typical on Earth). On Earth, such elongate bedforms are formed by subglacial sediment moulding and/or deposition beneath wet-based ice masses (Clark, 1994; Menzies, 1979). More specifically, terrestrial drumlins are almost exclusively associated with (a) high pore-water pressures within water-saturated subglacial sediments, and (b) strong longitudinal compression. Both of these conditions are met in the wet-based zone located immediately upglacier of the frozen margin of polythermal glaciers (Patterson and Hooke, 1995).

4.2.6. Rectilinear-ridge terrain

The rectilinear-ridge terrain (Fig. 13a) is similar in shape and appearance to two proglacial moraines on Earth: thrust-block (or push) moraines (Andrews, 1975) and moraine-mound complexes (Hambrey et al., 1997). Thrust-block moraines are formed by the transfer of stress in front of an advancing glacier, resulting in an *en echelon* arrangement of thrust plates that are aligned parallel to the advancing glacier margin and are most effectively (but not exclusively) created in front of frozen glacier margins. Thrust-block moraines are typically tens to hundreds of metres long and metres to tens of metres high, and are commonly characterised by preserved sedimentary structures and low-angle faults (e.g., Fitzsimons, 1997). The rectilinear ridges in front of the Hellas Planitia GLF are orientated similar to thrust-block plates, but they are smaller, being typically only some metres to tens of metres long and some metres high. In contrast, terrestrial moraine mounds are smaller,

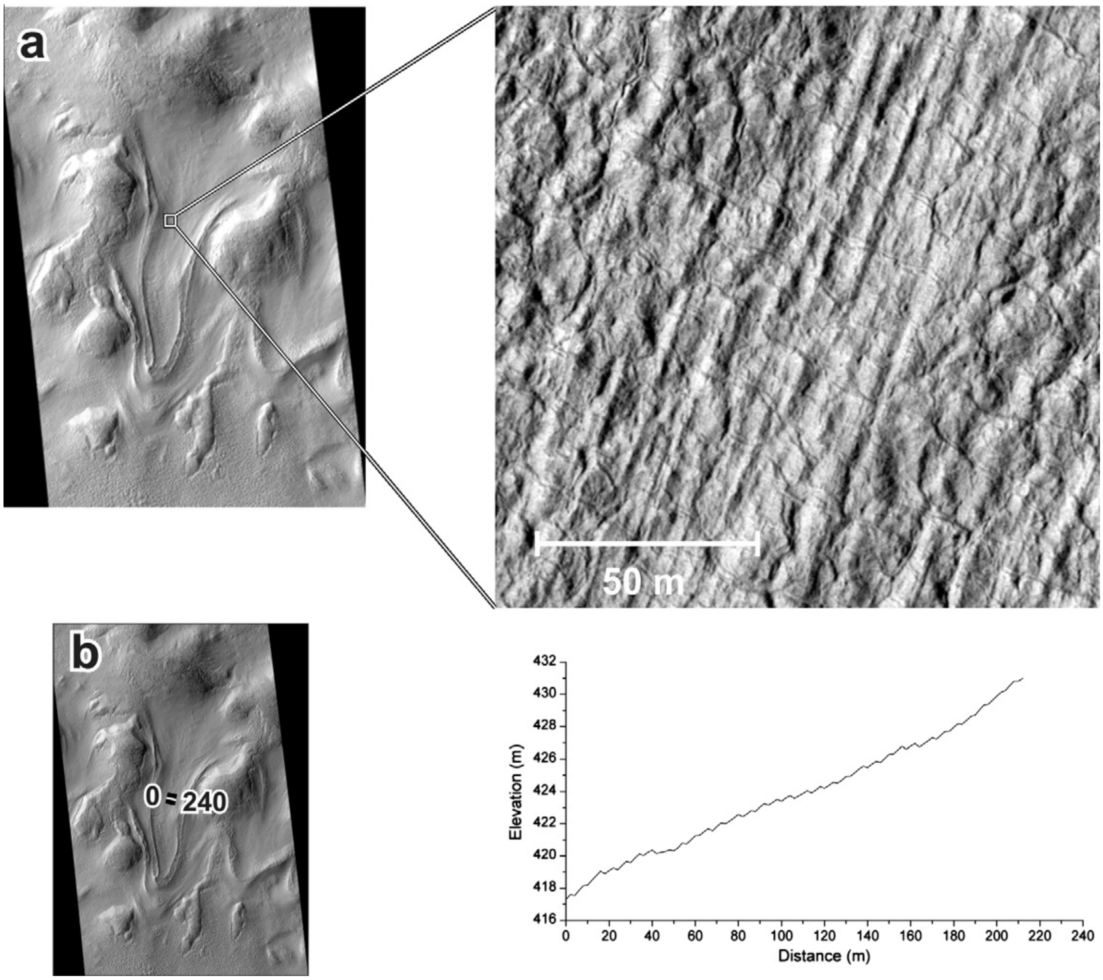

Fig. 10. Linear terrain. (a) Expanded HiRISE image illustrating linear terrain located in the middle and lower reaches of the martian GLF investigated in this study. (b) Transverse profile across a region of linear terrain. Note the regular roughness of the profile as it crosses individual lineations, each some decimetres high. The thumbnails indicate the locations of the expansion and surface profile in Fig. 1d.

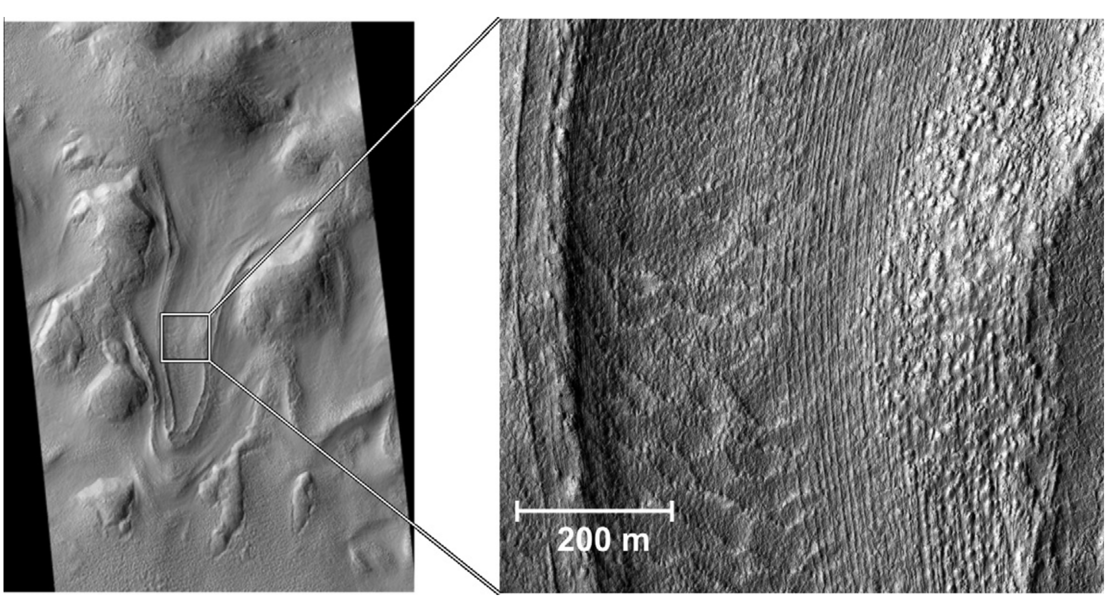

Fig. 11. Expanded HiRISE image illustrating the conformable bend in the linear terrain as it follows the bend in the GLF's tongue from a NNE–SSW orientation (upper image) to a N–S orientation (lower image). Note the geometrical and morphological continuity of the lineations and the mound-and-tail forms in the centre left of the image. The thumbnail indicates the location of the expansion in Fig. 1d.

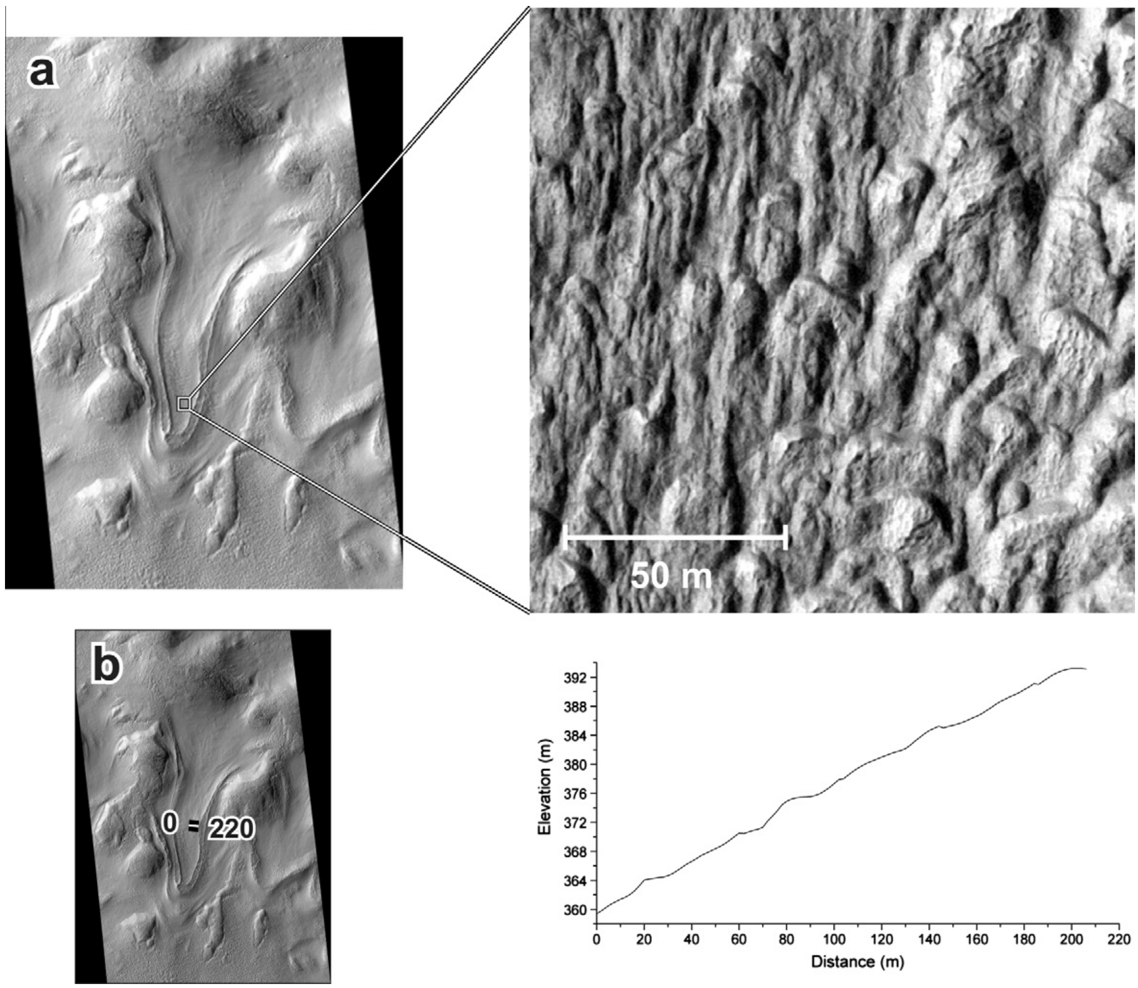

Fig. 12. Mound-and-tail terrain. (a) Expanded HiRISE image illustrating mound-and-tail terrain located predominantly near the terminus of the martian GLF investigated in this study. (b) Transverse profile across a region of mound-and-tail terrain. Note the subdued roughness elements in the profile as it crosses individual mounds, each a few metres high. The thumbnails indicate the locations of the expansion and surface profile in Fig. 1d.

and of a less regular geometrical configuration, than thrust-block moraines (Fig. 13c) – both more consistent with the Hellas Planitia GLF ridges. The possible origins of terrestrial moraine-mound complexes are disputed, but three contender processes – all involving the presence of liquid water – have been proposed: (a) as basal debris thrust up from the glacier bed (Hambrey et al., 1997), (b) as basal crevasse fills (Sharp, 1985), or (c) as ice-contact outwash deposits (Lukas, 2005).

Detailed sedimentological investigations would be required to identify definitively whether the Hellas Planitia rectilinear-ridge terrain is a thrust-block moraine or a moraine-mound complex (or some other, as yet unidentified, form). If it is a thrust-block moraine, then the ridges could have formed under any glacial thermal regime. However, the widespread extent of the terrain is more compatible with cold marginal ice than with warm marginal ice – signifying cold-based or polythermal glacial conditions. If the GLF's ridges are moraine mounds then they probably formed in the presence of warm ice – signifying wet-based or polythermal glacial conditions.

5. Synthesis and conclusions

5.1. Overview

Our detailed interpretation of one of several GLFs located in this region of eastern Hellas Planitia reinforces the existing general interpretation that mid- or low-latitude debris-rich GLFs on Mars have undergone geologically-recent glacial deformation (Head et al., 2003; Milkovich et al., 2006; Milliken et al., 2003). The lowering of this particular flow feature by up to some tens of metres relative to its bounding moraines, allied to the paucity of craters on its surface, indicates dramatic mass loss over the past 10^5–10^6 years. The nested sequence of at least four latero-terminal moraines bounding the feature implies, in the absence of evidence for any internal instability (such as surge-type activity), cyclical or punctuated variations in the processes that have controlled that mass loss.

5.2. GLF surface terrains

Four surface terrain types have been identified within the GLF's bounding moraines. These are, in order extending from the head of the feature to its terminus, scaly terrain (covering ~36% of the GLF's area), polygonized terrain (~25%), linear terrain (~22%), and mound-and-tail terrain (~15%). The remaining ~2% of the GLF's area is composed of indistinguishable sections of the inner slope of its bounding lateral moraine. In the upper basin, the scaly and polygonized terrains are characteristic of periglacial surface forms on Earth, with the former additionally suggesting substrate deformation. In the lower basin, the linear and mound-and-tail terrains are tentatively interpreted as elongate glacier-related bedforms which, if correct, implies water-lubricated basal motion

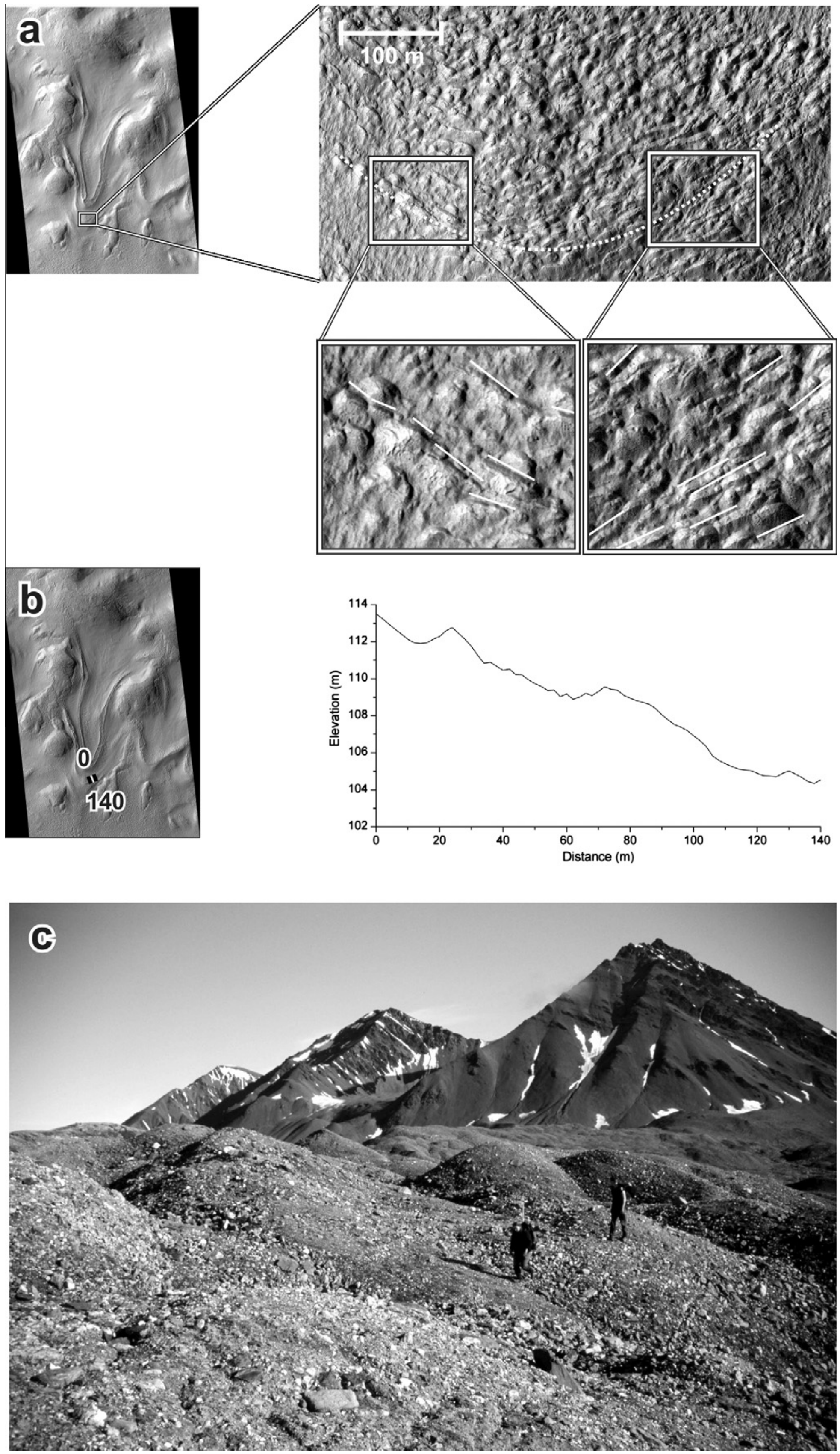

Fig. 13. Rectilinear-ridge terrain. (a) Expanded image (with two further expansions) of rectilinear-ridge terrain located within the outermost bounding ridge of the martian GLF investigated in this study. Individual rectilinear ridge elements are demarcated by superimposed white lines. (b) Longitudinal profile along a region of rectilinear-ridge terrain. The thumbnails indicate the locations of the expansion and surface profile in Fig. 1d. (c) Morphometrically-similar, terrestrial rectilinear moraine mounds located in the forefield of polythermal Austre Lovénbreen, Svalbard. Moraine-mound ridges are aligned parallel to the direction of the photograph, with the upglacier-facing rectilinear faces dipping to the right. Note figures in centre-right for scale. Photograph supplied courtesy M.J. Hambrey.

at the time of their formation. Patches of both linear and mound-and-tail terrain also occur sporadically in the GLF's upper basin.

5.3. Feature-scale interpretation

The surface terrain interpretations presented above are most consistent with a basin from which the (former) glacier has receded completely from its lower reaches (now leaving only exposed bedforms), while glacial material still exists in a degraded state (as dust-covered scaly and polygonized terrains) in the upper basin. This interpretation, however, must be tempered with the understanding that none of these terrains is dated – and they could be currently forming or relict. The images we interpret above also represent only a snapshot of a form that has doubtlessly experienced change, the rate of which remains unknown. Nonetheless, this situation – whereby active ice now occupies only the upper reaches of this GLF's former basin – is similar to almost all present-day glaciers on Earth (e.g., Benn et al., 2005). The presence of exposed bedform patches protruding through the superimposed scaly and/or polygonized terrain in the GLF's upper basin is consistent with this interpretation.

While we lack sufficient information to differentiate confidently between the physical properties of the recently or currently 'active' material in the upper basin and those of the 'residual bed material' in the lower basin, some tentative suggestions may be proposed on the basis of the descriptions and interpretations presented above. First, the surface terrains of the upper basin are sharper and 'fresher' looking than those of the lower basin. This suggests that the upper-basin scales and polygons are currently being formed or maintained, while the lower-basin lineations and mound-and-tail forms may have formed less sharply and/or are no longer being maintained in their original state in the face of current degradation at the martian surface. Indeed, the lineations appear to have been subjected to periglacial cracking since their formation. Second, boulder trails indicate that the surface of the scaly terrain (at least) appears to be formed from a decimetres-thick layer of unconsolidated sediment, possibly underlain by a more solid substrate. Third, the fine scale of the slope–parallel tilting of individual scales in the upper basin suggests that the underlying substrate is actively deforming, or at least deformed, up until the very recent past. All three of these interpretations are consistent with the upper basin being composed of a decimetres-thick mantle of unconsolidated surface dust overlying massive and recently-deformed and/or currently deforming (likely dust-rich) ice. This interpretation would also be consistent with recent radar-based evidence from MRO indicating the presence of near-surface ice within martian mid-latitude lobate debris aprons (e.g., Holt et al., 2008; Plaut et al., 2009). In contrast, the lower basin is characterised by more rounded and less fresh-looking glacial bedforms that show no evidence of recent erosion or deformation. This evidence is consistent with the lower basin material being formed from frozen ground in the absence of a massive, deforming layer of near-surface ice.

5.4. Implications for the thermal regime of GLFs

Two terrain types located in the GLF's lower basin (the linear terrain and mound-and-tail terrain) and one located within its frontal bounding moraines (rectilinear-ridge terrain) are consistent with formation or modification under partially wet-based glacial conditions, probably when the GLF was at its most recent maximum extent. Although alternative mechanisms of formation are possible for these terrains and further investigation is clearly needed, if polythermal conditions did exist in the geologically-recent past then it has important implications for modelling motion processes and interpreting the landform record at similar martian GLFs. In terms of the former, models of GLF motion may need to incorporate lubricated basal motion. In terms of the latter, landscape interpretation may need to account for streamlined depositional bedforms, sliding-related glacial erosion, and perhaps the products of subglacial drainage. While no erosional or drainage-related features have been identified by the present study, erosional grooves have been identified elsewhere on Mars and a broader investigation may now be timely. This could extend to larger martian VFFs which have previously been interpreted as ubiquitously cold-based.

Finally, key characteristics of two of the surface terrains associated with the GLF investigated herein (i.e., the troughs in the incised-headwall terrain and the extended cracks in the polygonized terrain) may have been associated with recent erosion by liquid water. Again, further research is necessary to strengthen or disprove this possibility but, if correct, it implies that surface snow or near-surface ice in and around the GLF's upper basin has melted in the geologically-recent past.

Acknowledgments

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