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Landscape evolution in Martian mid-latitude regions: insights from analogous periglacial landforms in Svalbard

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Abstract: Periglacial landforms on Spitsbergen (Svalbard, Norway) are morphologically similar to landforms on Mars that are probably related to the past and/or present existence of ice at or near the surface. Many of these landforms, such as gullies, debris-flow fans, polygonal terrain, fractured mounds and rock-glacier-like features, are observed in close spatial proximity in mid-latitude craters on Mars. On Svalbard, analogous landforms occur in strikingly similar proximity, which makes them useful study cases to infer the spatial and chronological evolution of Martian cold-climate surface processes. The analysis of the morphological inventory of analogous landforms on Svalbard and Mars allows the processes operating on Mars to be constrained. Different qualitative scenarios of landscape evolution on Mars help to better understand the action of periglacial processes on Mars in the recent past.

Many young landforms on Mars that were probably formed by exogenic processes show a latitude-dependent geographical distribution. They include surface mantling (Kreslavsky & Head 2000; Mustard *et al.* 2001; Morgenstern *et al.* 2007), lobate debris aprons, lineated valley fill and concentric crater fill (e.g. Squyres 1978), viscous flow features (Milliken *et al.* 2003), gullies (Balme *et al.* 2006; Kneissl *et al.* 2010) and patterned ground (Mangold 2005). Other landforms, such as pedestal craters, seem to indicate a preservation of near-surface ice and are also latitude-dependent (Kadish *et al.* 2009). Collectively, these landforms are hypothesized to represent the surface records of Martian ice ages (e.g. Head *et al.* 2003) that were induced by astronomical forcing (Laskar *et al.* 2004) and associated climate changes (Toon *et al.* 1980; Jakosky & Carr 1985; Mischna *et al.* 2003; Forget *et al.* 2006; Schorhofer 2007). Previous authors often considered only one of such feature classes in isolation (e.g. gullies), without taking into account the geomorphological context. It was not until the recent advent of high-resolution data from orbit and the *in situ* investigation of

Martian high-latitude terrain by the *Phoenix Lander* that a more integrated view of diverse landforms into a landscape evolution model were allowed to develop (e.g. Balme & Gallagher 2009; Levy *et al.* 2009a). A more comprehensive investigation of the full assemblage of landforms by means of landscape analysis, however, has the potential to reduce the ambiguity in interpreting landforms and to reveal the evolution of the climatic environment in more detail. The phenomenon of equifinality (i.e. similar-looking landforms resulting from diverse processes) is particularly problematic in planetary geomorphology, where the morphology as inferred from remote-sensing data such as images and digital elevation models (DEM) is the only observable component. An instructive example is the case of pitted mounds on Mars, which have been interpreted in the past as modified impact craters, rootless cones, cinder cones and pingos. In some of the studies that favoured pingos, the interpretations were based on poor evidence and attracted criticism from terrestrial permafrost researchers (Humlum & Christiansen 2008). Here we present permafrost landforms from Svalbard

(Norway) as useful terrestrial analogues for the suite of possible periglacial landforms that are typically found at mid-latitudes on Mars. We build on our previous investigations of gullies and fans (Hauber *et al.* 2009), and include a number of classical periglacial landforms (patterned ground, rock glaciers, pingos) that all have close morphological analogues on Mars. Based on this comparison, we propose several evolutionary scenarios that could help to develop a better understanding of the sequential formation of the Martian landforms.

Permafrost and periglacial features on Mars and Svalbard

Mars may be regarded as a permafrost planet, following the definition of permafrost given by van Everdingen (2005): ‘Ground (soil or rock [...]) that remains at or below 0 °C for at least two consecutive years, regardless of the water content’. In fact, the shallow subsurface of Mars probably experienced temperatures that were continuously below 0 °C for most of its history (e.g. Shuster & Weiss 2005). In the current Martian climate, ground ice is thought to be stable only at higher latitudes (e.g. Leighton & Murray 1966; Smoluchowski 1968; Fanale *et al.* 1986; Mellon & Jakosky 1993) and, indeed, the *Phoenix* mission has provided unambiguous evidence for very shallow and rather pure ground ice at a latitude of 68.2°N (Smith *et al.* 2009). The latitudinal range of ice stability is, however, a function of the planet’s obliquity (i.e. the tilt of the rotational axis). Mars’ obliquity is assumed to vary widely (Ward 1973; Touma & Wisdom 1993), and at an obliquity exceeding 32° (today *c.* 25°) ground ice becomes globally stable (Mellon & Jakosky 1995). An obliquity exceeding about 27° is required for ice to be stable at latitudes of 30° and higher (Mellon & Jakosky 1995, their fig. 10d). Other factors that affect the stability of ground ice are geographical variability, soil properties, rocks and local slopes (see Mellon *et al.* 2009 and references therein). The large and frequent oscillations of Mars’ obliquity (an obliquity cycle spans 117 000 years: Laskar *et al.* 2004) should have a significant influence on the volatile distribution on the surface (Jakosky *et al.* 1995), and climate modelling using global circulation models (GCM) confirms this view (Levrard *et al.* 2004; Forget *et al.* 2006; Madeleine *et al.* 2009). It appears likely that water ice was frequently driven from the poles towards lower latitudes during periods of higher obliquities, when the polar regions received more incoming solar energy (Forget *et al.* 2006). In contrast, water ice was redistributed towards higher latitudes during the following

periods of lower obliquities (Levrard *et al.* 2004). Ground ice can thus be expected to be a significant factor in Martian landscape evolution. Recent observations, indeed, showed that near-surface water ice is present even in mid- and low-latitude regions (Holt *et al.* 2008; Byrne *et al.* 2009; Vincendon *et al.* 2010*a, b*), in contrast to expectations from theoretical modelling (see above).

To complement theoretical modelling, comparisons with terrestrial analogues are mandatory to constrain the action of periglacial processes and the corresponding landscape evolution on Mars. Present-day Mars is cold and dry, so surface processes acting in terrestrial cold deserts should be considered as useful analogues. The closest cold-climate analogue to Mars on Earth are the Antarctic Dry Valleys (Anderson *et al.* 1972; Marchant & Head 2007, 2010), a polar desert environment with exceptionally cold and dry conditions (Doran *et al.* 2002) and correspondingly small active layer depth (Bockheim *et al.* 2007). Other polar regions also display morphological analogues to Mars, however, and the archipelago of Svalbard and its largest island, Spitsbergen (Fig. 1a), offer a diverse inventory of periglacial landforms in close spatial proximity. Terrain phenomena such as pingos, ice-wedge polygons and rock glaciers are widespread, especially in the dry central regions of Spitsbergen. Periglacial features such as solifluction lobes occur primarily in the more humid western regions. Various forms of patterned ground, such as stone circles and stripes, are widespread and well developed (see Åkerman 1987 for a review of periglacial landforms of Svalbard). Examples of periglacial morphologies are closely located to the settlements of Longyearbyen and Ny Ålesund on the main island of Spitsbergen, making them very useful morphological analogues to Martian cold-climate landforms. Major controls on permafrost aggradation are wind, snow and avalanches (Humlum 2005). A particularly interesting aspect of permafrost on Svalbard is its interaction with glaciers (Etzelmüller & Hagen 2005) because such interaction is often neglected in the literature (Haeberli 2005) but may be highly important on Mars.

Data

Martian surface features were analysed using high-resolution images of the CTX (Context Camera) and HiRISE (High Resolution Imaging Science Experiment) cameras, which have spatial resolutions of 5–6 m per pixel and approximately 30 cm per pixel, respectively. An airborne version of the HRSC (High Resolution Stereo Camera) was used for the acquisition of stereo and colour

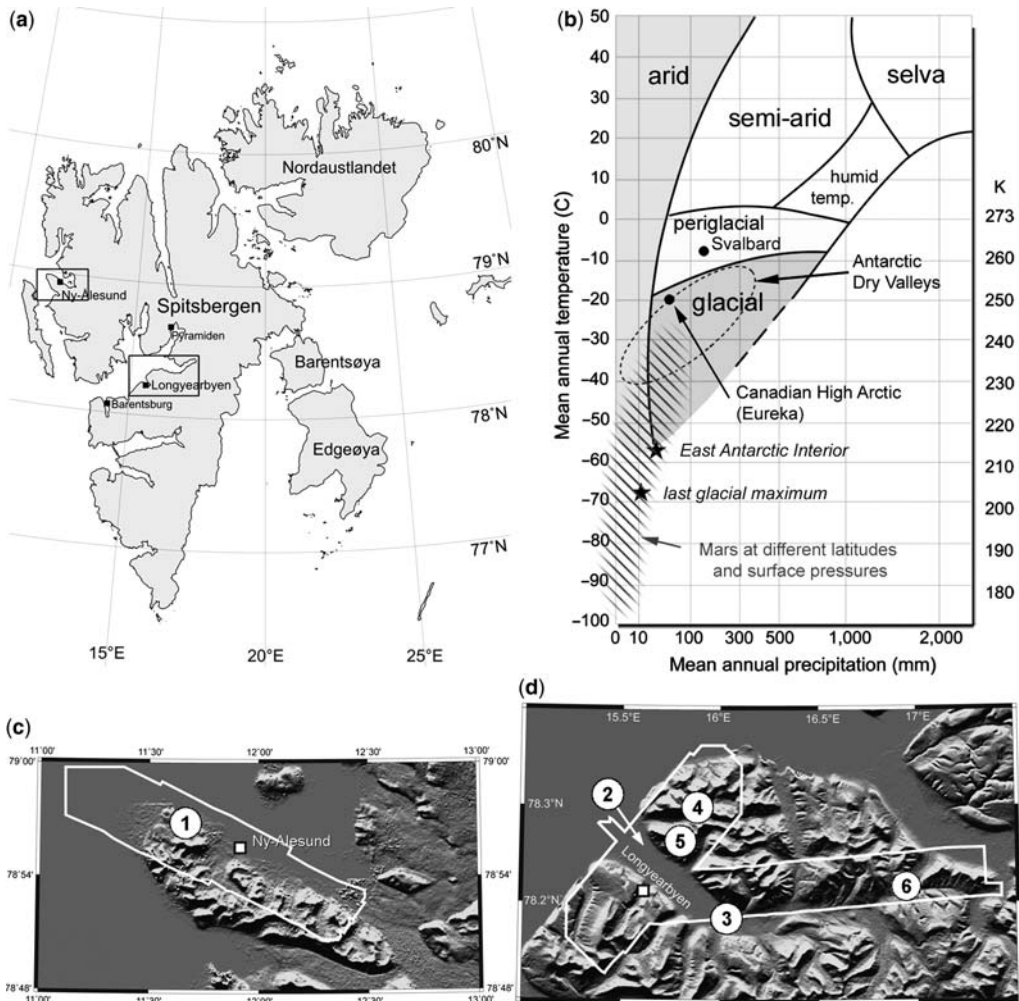


Fig. 1. Location and climate of study areas on Svalbard. (a) Map of Svalbard with study areas (boxes, see c and d). (b) Climate zones and morphogenetic regions on Earth; modified from Baker (2001) and Head & Marchant (2007). The climatic conditions on Mars (present and inferred past) are indicated by the hatched area. (c) Study area on the Brøgger Peninsula (shaded elevation model derived from ASTER data). (d) Study area in Adventdalen (shaded elevation model derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data). Numbers in (c) and (d) mark the geographical locations mentioned in the text: 1, Stuphallet; 2, Adventfjord; 3, Adventdalen; 4, Hannaskogdalen; 5, Hiorthfjellet; 6, Eskerdalen. Image credit: Univ. Münster/NASA/GSFC/METI/ERSDAC/JAROS/US-Japan ASTER Science Team; see prelim viii for acronym definitions.

images of Spitsbergen. HRSC-AX is a multi-sensor push broom instrument with nine CCD (charge-coupled device) line sensors mounted in parallel. It simultaneously obtains high-resolution stereo, multi-colour and multi-phase images. The particular value of HRSC-AX is the stereo capability, which allows it to systematically produce high-resolution digital elevation models (DEM) with grid sizes of between 50 cm and 1 m (Wewel *et al.* 2000; Scholten & Gwinner 2004; Gwinner *et al.* 2005, 2006, 2009, 2010; Scholten *et al.* 2005). The HRSC-AX

flight campaign in July–August 2008 covered a total of seven regions in Svalbard: (i) Longyearbyen and the surrounding area of Adventfjorden (all place names on Svalbard are as given as in the topographic map series, scale 1:100 000, published by the Norsk Polarinstitut, Tromsø, Sheets C9 and A7); (ii) large parts of Adventdalen; (iii) large parts of the Brøggerhalvøya (halvøya means peninsula) in western Spitsbergen; (iv) the Bockfjorden area in northern Spitsbergen; (v) the NE shore of the Palanderbukta and the margin of the adjacent ice cap in

Nordauslandet; (vi) an area on Prins Karls Forland; and (vii) the area of the abandoned Russian mining settlement of Pyramiden together with the nearby Ebbedal. The landforms discussed in this study are located on the Brøgger Peninsula and in Adventdalen and its vicinity (Fig. 1a). In two field campaigns in 2008 and 2009, both of the areas covered by HRSC-AX were visited.

The Svalbard climate

The present climate of Svalbard is arctic (Fig. 1b). The mean annual air temperature at the airport in Longyearbyen, which is located only a few kilometres from the study area of Adventdalen, ranges between about -6°C at sea level and -15°C in the high mountains (Hanssen-Bauer & Førland 1998). Annual precipitation is low and reaches only about 180 mm in central Spitsbergen (Table 1). The central part of Spitsbergen can, therefore, be considered to be a polar (semi)desert, which is defined as an area with an annual precipitation of less than 250 mm and a mean temperature during the warmest month of less than 10°C (Walker 1997). About 60% of Svalbard is covered by glaciers and ice caps, and relatively small glaciers and ice caps are situated on many massifs and valleys around Adventdalen. The unglaciated part of Svalbard is characterized by continuous permafrost, which has a thickness of 10–40 m in coastal regions, about 100 m in the major valleys and more than 450 m in the highlands (Liestøl 1976; Isaksen *et al.* 2000; Sollid *et al.* 2000).

Morphological comparisons between Mars and Svalbard

Many possible glacial and periglacial landforms are located in mid-latitude impact craters on Mars. This specific geological setting provides ideal study cases because there is high relief present at the crater walls, and the opportunity to study the effects of insolation variations because craters are axisymmetric features and their inner walls have an azimuthal range of the entire 360° . It has been found by many previous researchers that the pole-facing walls of impact craters are particularly prone to be shaped by glacial and periglacial processes (e.g. Dickson *et al.* 2007). In this section the inventory of such landforms is briefly reviewed and compared to analogous landforms on Svalbard. We note here that all of these features have been found in craters on Mars, sometimes several of them in the same crater but, so far, no crater has been found that hosts all of them together.

Martian landforms

Many landforms on Mars that are morphologically similar to terrestrial glacial and periglacial landforms occur in the middle latitudes, between about 30° and 60° (Fig. 2). They are situated along the high-relief belt of the Martian dichotomy boundary and other regions of high relief (e.g. Pierce & Crown 2003; Chuang & Crown 2005; Head *et al.* 2006; van Gasselt *et al.* 2010), as well as in flat-lying regions such as Utopia Planitia (Soare *et al.* 2005; Morgenstern *et al.* 2007; Lefort *et al.* 2009). A

Table 1. Climate at Svalbard Airport. For the series of observed and modelled annual and seasonal temperature means and precipitation sums from 1912 to 1993 the following values are given: mean, standard deviation, absolute minimum and absolute maximum. SD, standard deviation; Corr., correlation coefficient between observed and modelled temperature and precipitation series (data from Hanssen-Bauer & Førland 1998). For comparison, the mean annual air temperature at the floor of the Dry Valleys in Antarctica ranges from -14.8 to -30°C , and the mean annual precipitation is $\ll 100$ mm, but can be as low as 13 mm (Doran *et al.* 2002; Campbell & Claridge 2004)

Season	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Corr.
	Observed T ($^{\circ}\text{C}$)				Modelled T ($^{\circ}\text{C}$)				
Year	-6.3	1.7	-12.2	-3.1	-6.4	1.0	-8.9	-4.0	0.61
Winter (DJF)	-14.0	3.6	-23.2	-7.6	-14.1	2.4	-19.1	-9.1	0.62
Spring (MAM)	-10.8	2.4	-19.3	-6.7	-10.8	1.7	-15.2	-7.5	0.58
Summer (JJA)	4.3	0.7	2.5	6.1	4.2	0.5	3.2	5.4	0.54
Autumn (SON)	-4.8	2.0	-11.3	-1.3	-4.9	1.5	-8.7	-1.8	0.66
	Observed P (mm)				Modelled P (mm)				
Year	180.7	49.8	86.4	317.0	178.7	33.5	93.5	286.6	0.54
Winter (DJF)	53.4	24.3	16.8	140.0	52.8	11.5	24.5	86.8	0.40
Spring (MAM)	35.6	10.4	6.4	125.9	34.3	13.6	10.6	65.5	0.60
Summer (JJA)	43.7	21.2	3.0	114.0	43.7	18.7	8.3	100.8	0.57
Autumn (SON)	48.1	17.0	18.4	109.0	47.9	13.1	21.5	79.1	0.54

DJF, December, January, February; MAM, March, April, May; JJA, June, July, August; SON, September, October, November.

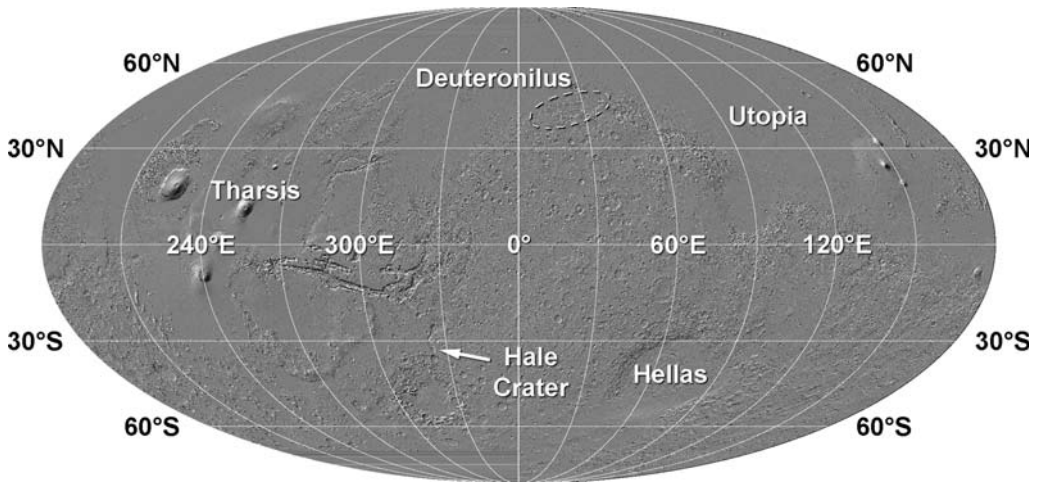


Fig. 2. Locations of regional features on Mars mentioned in the text (shaded version of the MOLA DEM). Image credit: DLR/NASA/JPL/MOLA Science Team.

particularly interesting setting is the pole-facing inner wall of impact craters. Most gullies (Fig. 3a) have been found on such walls, especially in the southern hemisphere (Dickson *et al.* 2007). On the base of some gullies, spatulate depressions are delineated towards the inner crater floor by arcuate ridges, which have been compared to moraines (e.g. Berman *et al.* 2005, fig. 1). Other landforms of possible periglacial origin have been observed in close spatial association with the crater-wall gullies, including polygons (Fig. 4a) (Levy *et al.* 2009c), patterned ground (Fig. 5a) (Mangold 2005), lobate features (Figs 6a & 7a) (Milliken *et al.* 2003) and fractured mounds (Fig. 8a)

(Dundas *et al.* 2008). The unique occurrence of diverse possible periglacial landforms within a small area with considerable relief makes such craters an ideal study case for the action of periglacial processes on Mars. In the following, they will be compared with terrestrial analogues on Spitsbergen. Based on this comparison, possible scenarios of landscape evolution on Mars will be outlined.

Svalbard landforms

The main study site is Adventdalen, an approximately 40 km-long and up to about 3 km-wide valley in central Spitsbergen, that was deglaciated

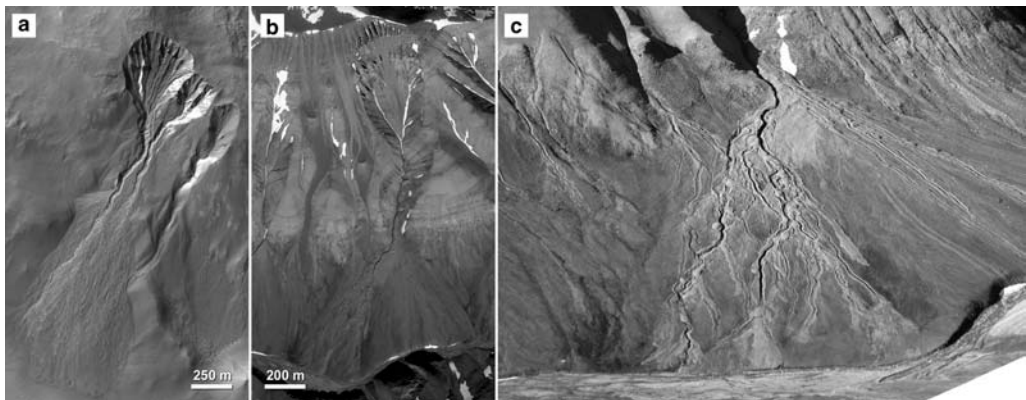


Fig. 3. Gullies and fans on Mars and Svalbard. (a) Gully in Martian crater at 38.5°S, 319.8°E (HiRISE PSP_006888_1410). (b) Gully and debris-flow fan in Hannaskogdalen, Svalbard. Note the similarity in morphology and scale between the two systems. (c) Close-up field photograph (taken from the opposite mountain) of the fan surface shown in (b). Note the morphological indicators of debris flows, such as large lateral levees and flow tongues. Image credit: NASA/JPL/UoofA, DLR and Univ. Münster/Mike Zanetti.

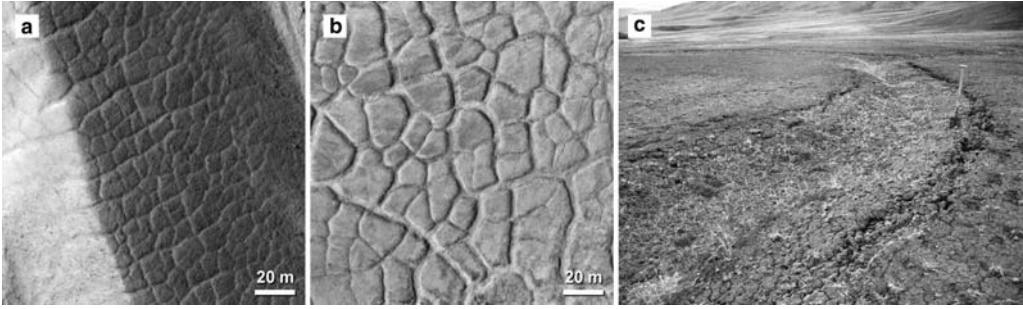


Fig. 4. Polygons on Mars and Svalbard. (a) Oriented-orthogonal polygons pattern on a ridge between two gullies on the northern wall of Hale Crater, Mars. The polygons have high centres and diameters between about 5 and 10 m (HiRISE image PSP_004072_1845; near 34.6°S, 323.1°E). (b) High-centre orthogonal polygons in central Adventdalen (HRSC-AX image). The polygons have high centres, and diameters between approximately 10 and 20 m. A trough that is typical for this type of polygon is shown in panel (c). (c) Trough between high-centre polygons in central Adventdalen. Note the fractured and degraded appearance of the trough shoulders. Spade for scale. Image credit: NASA/JPL/UofA, DLR and AWI/Mathias Ulrich.

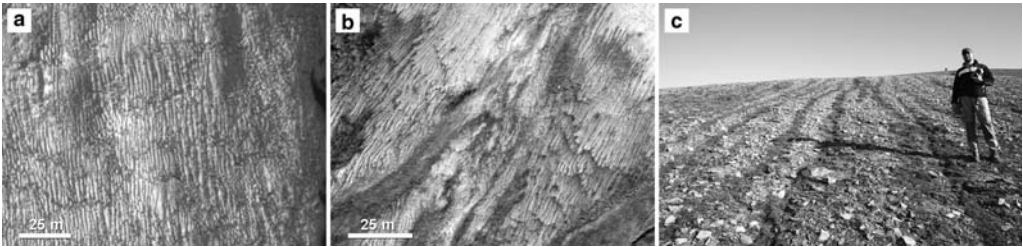


Fig. 5. Comparison between alternating bright and dark stripes on Mars and sorted stripes on Svalbard. (a) Alternating dark and bright stripes near gullies on the inner wall of a Martian impact crater (HiRISE image PSP_001684_1410; near 38.9°S, 196.0°E). The orientation of the stripes is approximately downslope. (b) Sorted stripes on the western slopes of the Hiorthfjellet massif (east of Adventfjorden, Spitsbergen). Note the striking similarity in scale between (a) and (b). (c) Sorted stripes in Adventdalen (Spitsbergen). Coarser and slightly elevated unvegetated stripes alternate with finer-grained and vegetated stripes (person for scale). Image credit: NASA/JPL/UofA, DLR and DLR/Ernst Hauber.

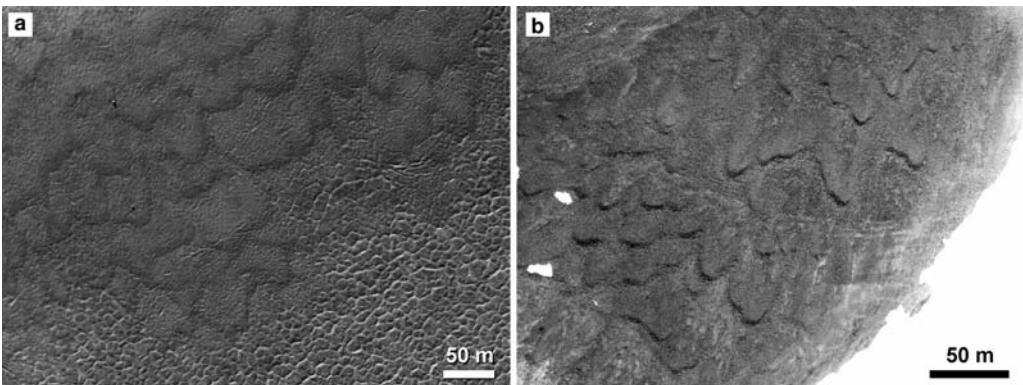


Fig. 6. Comparison between lobate structures on Martian slopes and solifluction features on Svalbard. (a) Lobate features on the inner wall of an impact crater on Mars (near 71.9°N, 344.5°E; HiRISE PSP_010077_2520). The morphology is identical to that of lobate solifluction sheets (cf. Ballantyne & Harris 1994, fig. 11.1). Although this particular example is on the wall of a crater in high latitudes, it is expected that such features might also be found in mid-latitude craters. (b) Solifluction lobes on the slopes of Louisfjellet (central Spitsbergen, Svalbard). Note the striking similarity in scale and morphology between (a) and (b). Image credit: NASA/JPL/UofA and DLR.

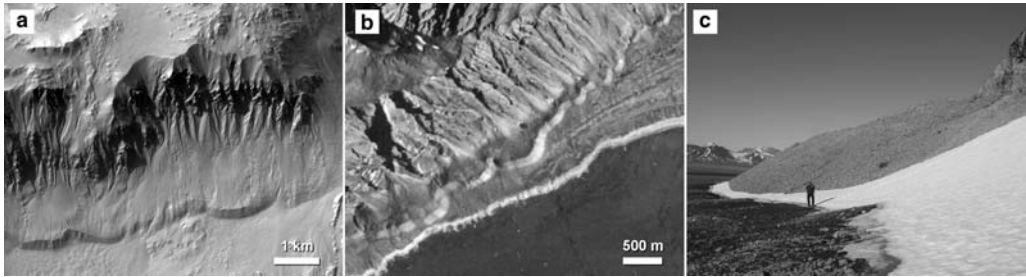


Fig. 7. Possible protalus ramparts on Mars (left) and Svalbard (right). (a) Protalus lobe-like structures at the base of a large scarp on the northern wall of Hale Crater (CTX image P15_006756_1454; near 34.6°S, 323.1°E; north is up). The steep front is characterized by polygons (see Reiss *et al.* 2009; their fig. 10b, c). (b) Protalus lobes on the northern tip of Prins Karls Forland, Svalbard (see Berthling *et al.* 1998), at the western foot of the Fuglehukfjellet massif (aerial photograph S704128, Norsk Polarinstittutt, Oslo, Norway; from André (1994); north is towards the left). (c) Close-up image of a protalus rampart at Stuphallet, Brøgger Peninsula (see person for scale). The surface of the steep front consists of very coarse blocks (diameters of up to tens of centimetres). Image credit: NASA/JPL/MSSS and Univ. Münster/Dennis Reiss.

about 10 000 years ago (Mangerud *et al.* 1992). The valley hosts a large number of periglacial landforms, both on the valley flanks and on the valley floor. The mountain massifs and the upper parts of many valleys are still partly covered by polythermal or cold-based glaciers, which can be partly debris-covered (Tolgensbakk *et al.* 2000). Distinctive end moraines, which may be ice-cored (Lukas *et al.* 2005), mark the former larger extent of the glaciers. Some tongue-shaped rock glaciers are perched in cirques and broad alcoves (Isaksen *et al.* 2000; Ødegård *et al.* 2003). Protalus ramparts, defined as ‘ridges or ramps of debris formed at the downslope margin of a snowbed or firn field’ (Shakesby 1997, p. 395), are well developed on the foot of high cliffs on the Brøgger Peninsula (Fig. 7b, c). Rock fall is frequent from the steep cliffs that mark the flat-topped summits of the

mountains (André 1995). The flanks of the massifs bordering the valley are dissected by numerous gullies (Fig. 3b, c), which are the transport pathways for debris flows. Debris flows can reach volumes of 50–500 m³ in the Longyearbyen Valley (Larsson 1982), and their recurrence interval is 80–500 years (André 1990). Between the gullies, many slopes display evidence of solifluction (Fig. 6b) and sorting processes (sorted and non-sorted nets and stripes: Fig. 5b, c) (Sørbel & Tolgensbakk 2002). The debris flows build up fans, characterized by channels with lateral levees, flow tongues and coarse sediment (for a description of an alluvial fan in a permafrost region see Catto 1993). Where fans extend to the shore of the estuary at the mouth of Adventdalen, they can form an arctic fan delta (Lønne & Nemeč 2004). In the inland, debris-flow fans at the downstream-end of the gullies coalesce

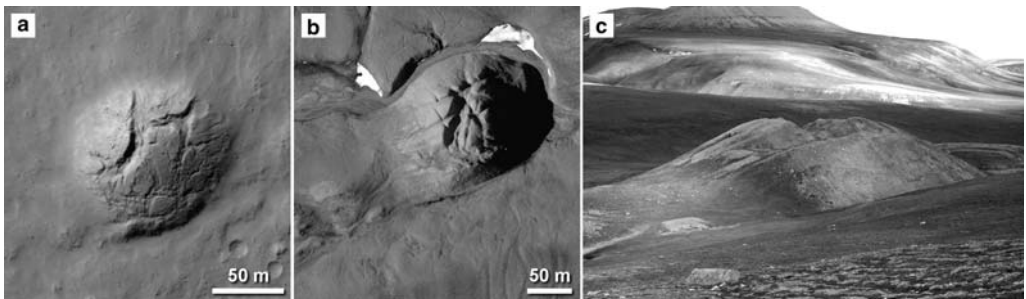


Fig. 8. Comparison between a fractured mound on Mars and pingo on Svalbard. (a) Fractured mound on the floor of a crater in the southern hemisphere (detail of HiRISE image PSP_007533_1420; near 37.9°S, 347.2°E: see Dundas & McEwen 2010). (b) Pingo in upper Eskerdalen (central Spitsbergen) with fractures on its top. HRSC-AX image, acquired in July 2008. Note the morphological similarity to the shallow fractured mound shown in (a). (c) Field photograph of pingo shown in (b). North is up in panels (a) and (b). View towards the NE in panel (c). Image credit: NASA/JPL/UofA, DLR and DLR/Ernst Hauber.

along the valley to form bajadas. The valley floor is occupied by the large braided river, Adventelva, which often cuts the toes of the fans. Several open-system (hydraulic) pingos are located near the fans on the valley floor (Fig. 8b, c) (Liestøl 1976; Yoshikawa 1993; Yoshikawa & Harada 1995). River terraces are overprinted by thermal-contraction cracks that form widespread nets of ice-wedge polygons (Fig. 4b, c) (Christiansen 2005). Most of the landforms on the valley flanks can be considered to be part of an ice-debris transport system, where mass wasting takes place both by steady-state processes (small-scale rockfall, avalanches, glacial and fluvial transport and solifluction) and by more extreme short-lived processes (large-scale rockfall, landslides, debris flows) (Haerberli 1985). Figure 9 demonstrates the spatial arrangement of the landforms in Adventdalen in an idealized sketch, and Figure 10 shows a three-dimensional perspective view of the Hiorthfjellet massif exhibiting some of the features in their real setting.

Discussion

The above comparisons suggest that periglacial processes might have operated in Martian mid-latitude

craters. However, the exact nature, intensity and sequence of these processes are unclear. We present three different models that outline in a qualitative way some possible scenarios of how mid-latitude craters were shaped in the recent Martian history by processes involving water ice and, to a lesser degree, liquid water. It is important to note that these models are not thought to be mutually exclusive, nor do they necessarily include all processes that operated on Mars. Instead, they are suggested as examples of how planetary landform analysis guided by terrestrial knowledge can yield improved insight into the evolution of complex landscapes.

The premise of the models is that during higher obliquity water ice is driven from the poles towards lower latitudes where it is precipitated as snow. During periods of lower obliquities, the precipitated snow would sublime or melt, and water vapour would be redistributed at higher latitudes. This basic pattern of volatile transport through the atmosphere as a function of obliquity has been modelled with GCM (Mischna *et al.* 2003; Levrard *et al.* 2004; Forget *et al.* 2006; Madeleine *et al.* 2009), and the modelling results successfully predict ice accumulation in places where, indeed, an increased frequency of possible glacial landforms have been

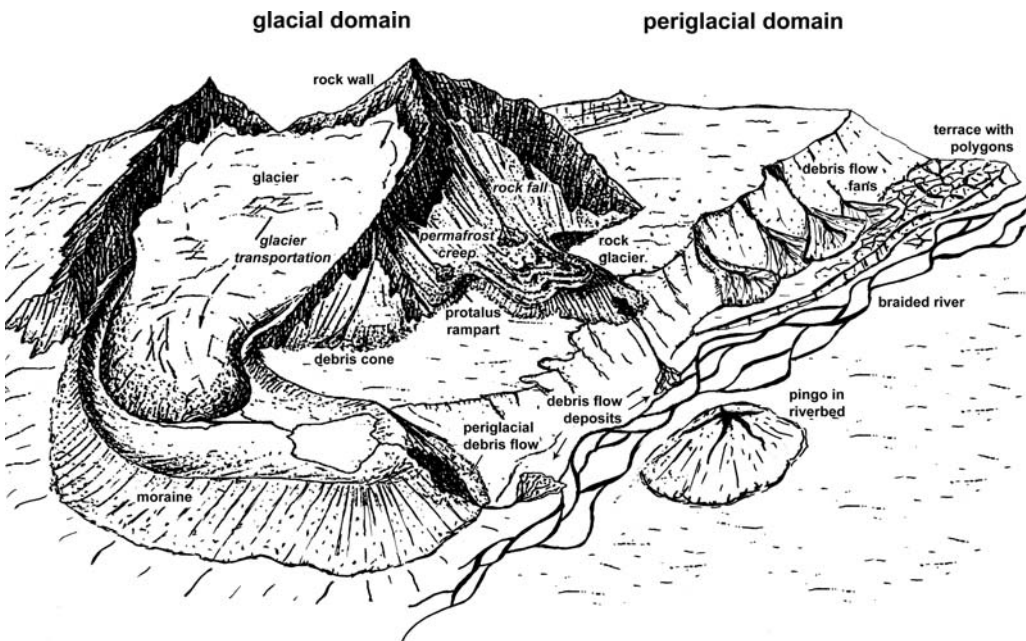


Fig. 9. Ensemble of glacial and periglacial landforms observed in Adventdalen (central Spitsbergen, Svalbard; modified from Haerberli, 1985, fig. 1). The qualitative sketch is not meant to represent the real situation in Adventdalen, but to illustrate the spatial arrangement of the landforms. Morphologically similar landforms have been observed in Martian mid-latitudes craters, often in comparably close spatial proximity. The unique advantage of such terrestrial analogues is their potential to provide constraints in the interpretation of planetary surface morphologies.

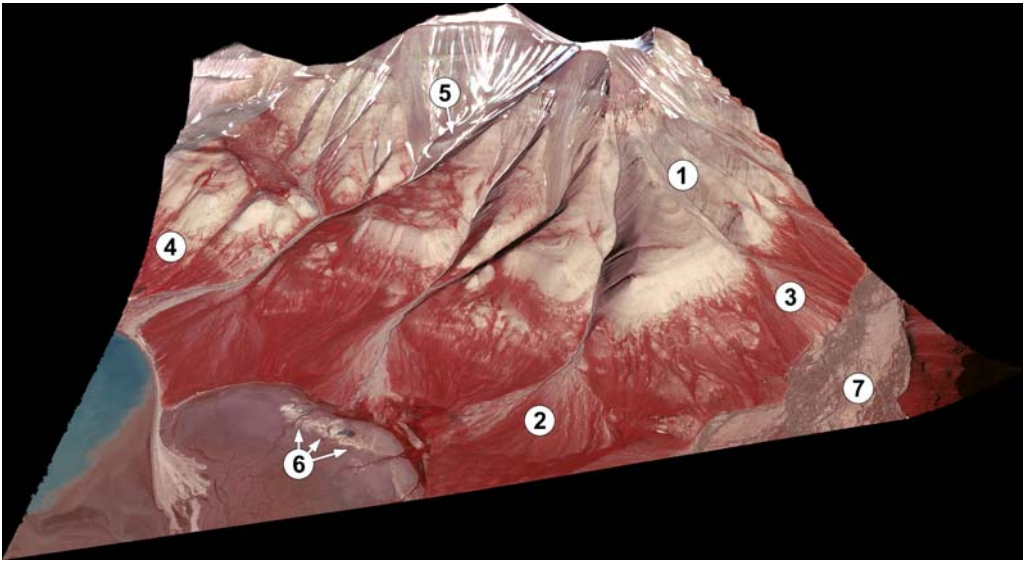


Fig. 10. Example of the close spatial proximity of glacial and periglacial landforms on Svalbard. The scene (width *c.* 3.7 km; north is towards the background) was computed from HRSC-AX false-colour stereo images and shows the Hiorthfjellet mountain massif on the northern side of Adventfjord. Numbers refer to specific landforms: 1, gullies; 2, alluvial fan; 3, debris-flow fans merging along the valley wall into a bajada; 4, slope stripes; 5, rock glacier; 6, pingo; 7, braided river. All of these landforms with the exception of the braided river have close morphological analogues in Martian mid-latitude craters. Image credit: DLR.

observed (e.g. east of the Hellas Basin, west of the Tharsis Montes and at the Deuteronilus Mensae region). If this premise is accepted, it implies that the pattern of deposition and degradation of snow and the associated periglacial processes operate in cycles, as the obliquity varies cyclically. One of such cycles is discussed in the following for each of the scenarios.

Following the scheme of landscape evolution proposed by Morgenstern *et al.* (2007) for the lowlands of Utopia Planitia, the initial process in the cycle of deposition and degradation is the subaerial deposition of a volatile-rich mantle consisting of a layered mixture of dust and snow. Martian dust is suggested to originate from volcanic sources, meteoritic impact and rock erosion, and is redistributed by global dust storms (Kahn *et al.* 1992). The dust particles act as condensation nuclei for water ice (H₂O-ice: e.g. Gooding 1986). The dusty snow mantle would be thicker at the pole-facing wall, but would also cover the crater interior and smaller crater therein. This stage is common to all three scenarios (Fig. 11a–c, stage I). Such a mantling deposit had already been suggested on the basis of *Mariner 9* data (Soderblom *et al.* 1973), and was later revealed in detail by high-resolution topography (Kreslavsky & Head 2000) and images (Mustard *et al.* 2001). This mantling layer has a thickness of the order of tens of metres in lowlands

(Morgenstern *et al.* 2007), but it is not clear how much of this thickness is deposited during one obliquity cycle. The microclimatic conditions at pole-facing (inner) walls of craters are such that ice is preferentially accumulated and preserved in these locations, that is, they function as cold traps for atmospheric water ice (Hecht 2002; Schorghofer & Edgett 2006; Head *et al.* 2008).

The 'dry' scenario

Over time, the accumulated snowpack would increase in thickness and eventually the lower portions would transform into glacier ice (Fig. 11a, stage II). This glacier would probably contain a significant amount of dust (and perhaps wind-blown sand, but no or very few rock fragments) and we tentatively suggest the term 'dust glacier'. The plan-view shape of such glaciers would typically be tongue-shaped (length > width), as it is commonly observed on Earth (for a comparison between these shapes on Mars and Earth, see Arfstrom & Hartmann 2005, their fig. 2). If it were cold enough, this glacier would freeze onto the underlying crater wall and be a cold-based glacier, as has previously been suggested for Mars (Head & Marchant 2003). A cold-based glacier would cause little or no erosion of the underlying crater wall and, therefore, the slope of this wall might remain

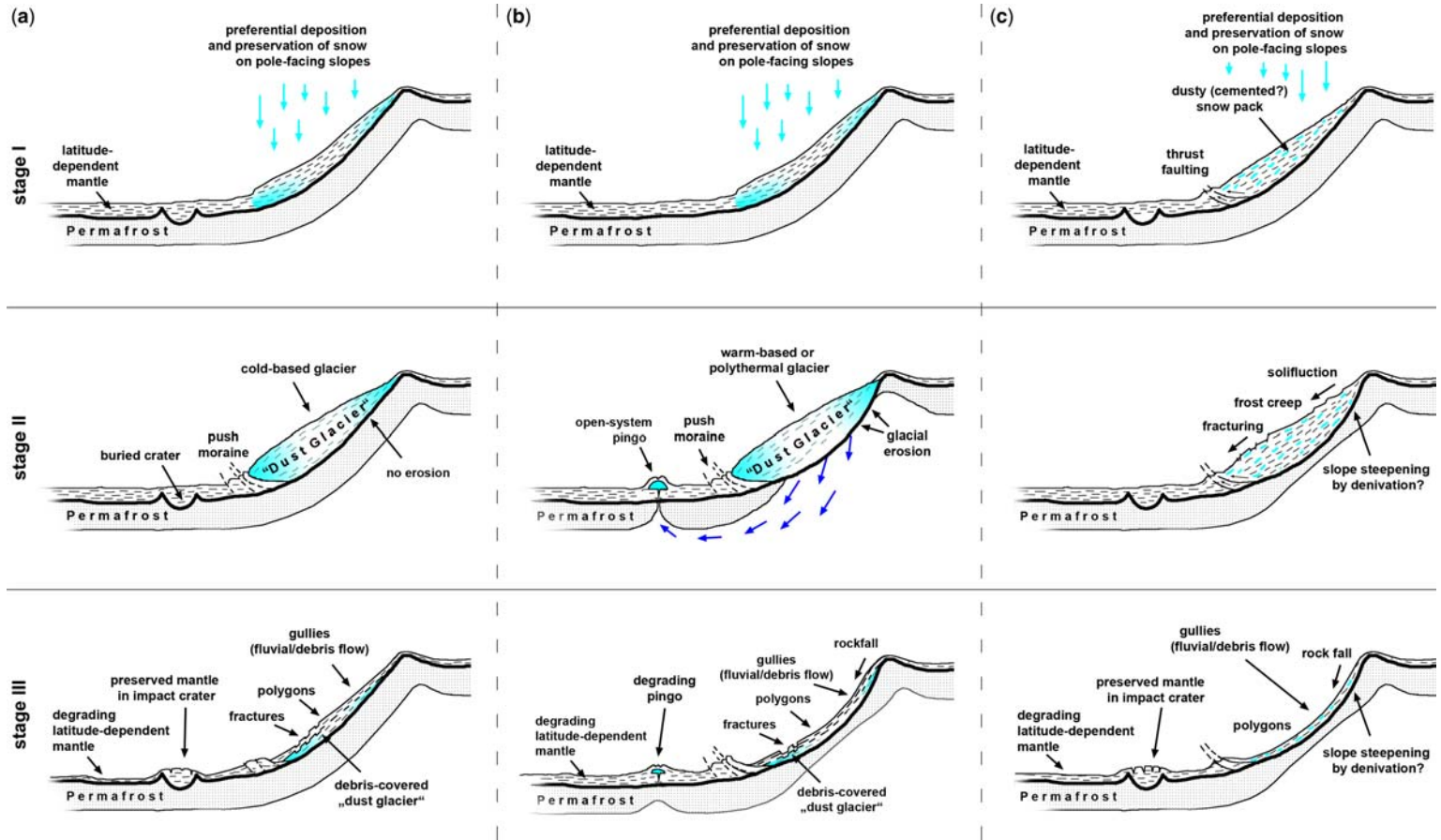


Fig. 11. Qualitative scenarios of landscape evolution in Martian mid-latitude craters. See the text for details.

more or less unchanged. At the downslope termination of the glacier, thrust or push moraines could develop (e.g. Berman *et al.* 2005) because even if there was no basal sliding of the glacier it would deform internally and move downslope. The presence of push moraines in front of cold-based glaciers has been well documented on Earth (e.g. Haeberli 1979), where push moraines are the morphological result of permafrost deformation. These moraines would be piled up to form ridges, which might contain some ice. In some cases, a lobate body might form at the base of the crater wall that has a width larger than its length (Fig. 7a). This class of flow feature exhibits a striking large-scale similarity to protalus ramparts on Svalbard (Fig. 7b). The spatial proximity of 'dust glaciers' (ice-cored), moraines and permafrost features, such as protalus ramparts, would not be surprising because it was suggested that these landforms might be part of a morphological and developmental continuum (Shakesby *et al.* 1987). At smaller scales of observation, however, significant differences become obvious between the Martian and terrestrial features shown in Figure 7. The steep distal front of the Martian flow feature is overprinted by polygons (cf. Reiss *et al.* 2009, fig. 10), which are likely to have been developed as thermal contraction cracks in fine-grained material. In contrast, the distal fronts of the protalus ramparts on Svalbard consist of coarse, decimetre-sized rocks derived from steep cliffs and mountain slopes. The difference is easily explained, however, if the relief above the features is taken into account. On Svalbard, the slopes are steep and frequent mass wasting delivers copious amounts of coarse particles, which form the rocky part of the rock glacier. Conversely, the lower slopes of large and old craters on Mars (such as Hale Crater, in the example of Fig. 7a) are much gentler, and the material being mixed with ice to form the protalus rampart-like feature would be fine-grained airborne dust. On the surface of such a body, it would be reasonable to expect the formation of sublimation polygons.

After the obliquity decreases, the ice would slowly become unstable and begin to sublimate. A lag deposit of dust and sand would form at the top of the glacier, decreasing the rate of sublimation (Mellon & Jakosky 1993; Chevrier *et al.* 2007). Internally, the glacier might still be deformed. If the lag deposit has some cohesion (e.g. from cementation), the ongoing internal deformation of the glacier body might crack the lag deposit and form tension fractures, normal faults and grabens paralleling the topographical contours. When sublimation would have removed most of the ice, a thick and very fine-grained lag deposit (dominated by dust-sized particles) would remain above a thinned body of buried glacier ice. At the same time, the

mantling deposit in the crater interior would also degrade and become thinner. Where this mantling filled a smaller impact crater, it might be preferentially preserved, leaving a high-standing mound of the mantling that could develop fractures at its top. As Dundas & McEwen (2010) have already discussed, such a fractured mound could easily be misinterpreted as a pingo (Fig. 11a, stage III). Thermal contraction polygons could develop in the sublimation lag. By analogy to the McMurdo Dry Valleys in the Antarctica, these polygons could be sublimation polygons (Marchant *et al.* 2002), as suggested for Mars by Levy *et al.* (2009b). It has to be noted, however, that the exact nature of the polygons (ice-wedge polygons, sand-wedge polygons or sublimation polygons) remains an open question as the morphology alone does not allow for an unambiguous identification of either of these forms (e.g. van Gasselt *et al.* 2005). For example, degraded ice-wedge polygons in Adventdalen (Fig. 4b, c) display a morphology that can hardly be distinguished from sublimation polygons in remote-sensing imagery. With continual degradation, the volume of the remaining ice would be so small that scalloped depressions would form between the thrust moraines, left behind as arcuate ridges, and the remaining lag deposit on the crater walls (Fig. 11a, stage III). Remnant thicker patches of near-surface ground ice (Costard *et al.* 2002) or snow perched high in alcoves on the crater rim (Head *et al.* 2008) might finally melt (Hecht 2002; Kossacki & Markiewicz 2004). The meltwater could run off surficially and initiate fluvial transport and downstream deposition, where a resulting alluvial fan would form (Fig. 11a, stage III). Alternatively, the meltwater could infiltrate into the lag deposit, saturate it, increase the pore pressure and thus reduce its shear strength, which would increase the susceptibility of the material to gravity-driven failure and debris flows (e.g. Iverson *et al.* 1997). The degree of saturation is commonly increased if a low-permeability layer in the subsurface is present, which leads to the transient perching of the water table (Reid *et al.* 1988), and the frozen underground would be such a hydrological barrier. Another factor favouring the development of debris flows in this setting on Mars is the small grain size of the lag deposit because clay-sized material is required to maintain the high pore pressures needed during the flow (Iverson 1997). This mechanism of debris-flow initiation has also been proposed by Lanza *et al.* (2010). Unambiguous evidence for debris or mud flows on Mars has, indeed, been found by Levy *et al.* (2010). The debris flows and the fluvial processes would form a downstream fan, as is typical for Earth. The fans have been dated by crater counting and have ages

of the order of 10^5 – 10^6 years (Reiss *et al.* 2004; Schon *et al.* 2009a). In the ‘dry’ model, a transition takes place from glacial to periglacial processes, and the formation of gullies and fans from and on the lag deposit would be the final stage (Dickson & Head 2009).

The ‘wet’ scenario

The second scenario starts as the ‘dry’ one, except that a warm-based or polythermal ‘dust glacier’ would form. This glacier would experience basal

melting and, therefore, the ice and subglacial melt-water would erode and steepen the crater wall (Fig. 11b, stage II). Another difference to the first scenario would be the extent of the permafrost layer. Beneath the warm-based glacier, the permafrost would disappear and liquid water generated by the basal melting of the glacier would infiltrate into the substrate. A similar scheme was proposed by Carr & Head (2003) and Fassett & Head (2006). The groundwater would migrate down towards the interior of the crater. In the subsurface of the crater floor, beyond the extent of the

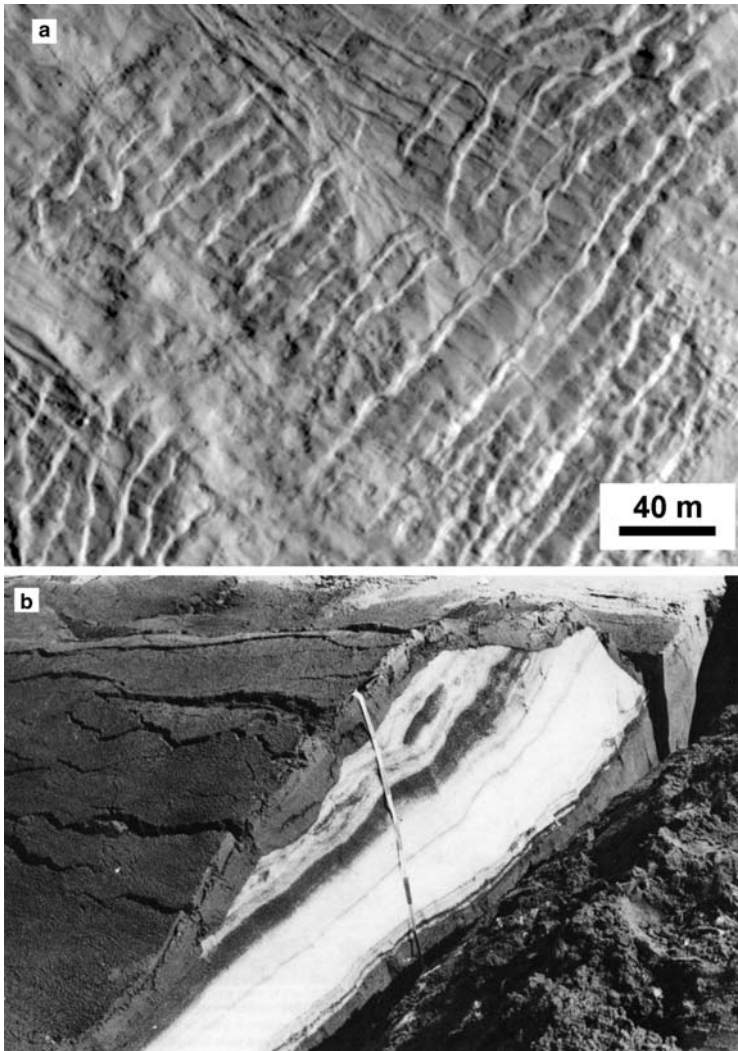


Fig. 12. (a) Extensional features (normal faults and grabens) trending normal to the topographical gradient of the inner wall of an impact crater in the northern mid-latitudes (near 39.5°N , 105.4°E ; detail of HiRISE PSP_001357_2200, north is up). (b) Niveo-aeolian sediment at the lee (slip) side of a transverse dune in the Great Kobuk Sand Dunes (NW Alaska, USA; from Koster (1988), photograph by J. Dijkmans). Image credit: NASA/JPL/UofA and J. Dijkmans.

glacier, there would be an impermeable permafrost layer above the groundwater, and the hydraulic head would pressurize the groundwater. At weak spots in the crater floor, which would be abundant owing to the fracturing that was created at the impact, this groundwater could ascend as artesian water. Reaching the near surface, it would freeze and build a growing ice core. With time, a mound consisting of this ice core and some overlying mantle deposit would rise. This is how hydraulic (open-system) pingos grow on Earth, except that they do not form in craters, but rather in valleys where the hydraulic head has its source in nearby mountains (Müller 1959; Worsley & Gurney 1996; Mackay 1998). The pingos in the study area in Spitsbergen are also thought to form by this mechanism (Liestøl 1976, fig. 2). If the same process applies to Mars, it would represent an example of glacier–permafrost interaction, which is also considered to be an important factor in landform evolution on Svalbard (Etzelmüller & Hagen 2005). The steepening of the crater wall by glacial erosion would increase the probability for rockfall, which was suggested as a triggering mechanism for debris flows on Earth if the other requirements (saturated soil, positive pore pressure) are met (Hsu 1975; Johnson 1995). Apart from these differences, this ‘wet’ scenario would otherwise be very similar to the ‘dry’ scenario, and glacial processes (including surficial meltwater production and runoff: Fassett *et al.* 2010) would be followed by the formation of periglacial landforms (polygons, solifluction lobes, rock glaciers and pingos) and, finally, paraglacial processes (avalanches, rock falls, debris flows,

chemical denudation, mechanical fluvial denudation and surface movements/creep) (Fig. 11b, stage III).

The ‘snow’ scenario

A thick snowpack might form instead of a glacier in the ‘snow’ scenario (Fig. 11c, stage I). The transition of snow (or rather firn) to glacier ice is defined by density and starts at approximately 830 kg m^{-3} , where interconnecting air passages between ice grains become sealed off (Paterson 1994) and reach a final value of 917 kg m^{-3} (Knight 1999, table 3.3; for an extended discussion of ice metamorphism, firnification and ice formation see Shumskii 1964, pp. 240–303). While it is known that many factors (e.g. vapour transport, and the diurnal and seasonal temperature variations) control the snow densification on Mars (Arthern *et al.* 2000), a clear difference between Earth and Mars is the rate of gravity-driven snow densification (sintering). Other factors being equal, the transition from snow (or rather firn) to glacier ice should, therefore, occur on Mars at a greater depth than on Earth (the Martian gravitational acceleration at its surface is about 38% of that on the Earth’s surface). Typical values for this depth on Earth are approximately 10–20 m in temperate areas and much less than 50 m in cold continental areas (e.g. Shumskii 1964, p. 275). The timescales of this transformation are also vastly different, depending on the climate. In cold and dry climates, such as in Antarctica, the transformation may require up to 2500 years (Paterson 1994, table 2.2), whereas it can be as short as only a few years in

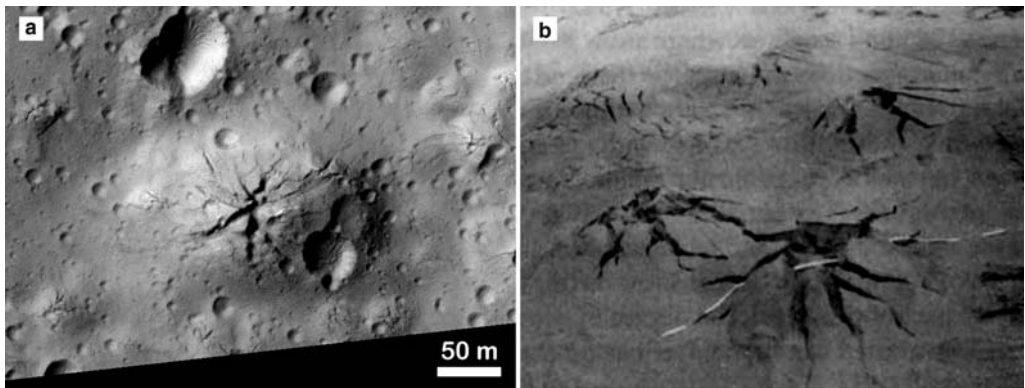


Fig. 13. Comparison between fractured mound on Mars and niveo-eolian features on Earth. (a) Mound with radial fractures on the floor of an impact crater in the southern mid-latitudes. The surface of the mound is superposed by several round depressions that might be due to collapse and/or impact cratering (near 33.6°S , 124°E ; detail of HiRISE PSP_002135_1460; north is up). (b) Snow hummock with radial tensional cracks on the Great Kobuk Sand Dunes (Alaska, USA; from Koster & Dijkmans 1988). The hummock is a denivation form that developed in niveo-eolian beds. Note the morphological similarity to (a), but also note the large difference in scale (these hummocks are only a few decimetres to 1 m wide). See the text for details. Image credit: NASA/JPL/UofA and J. Dijkmans.

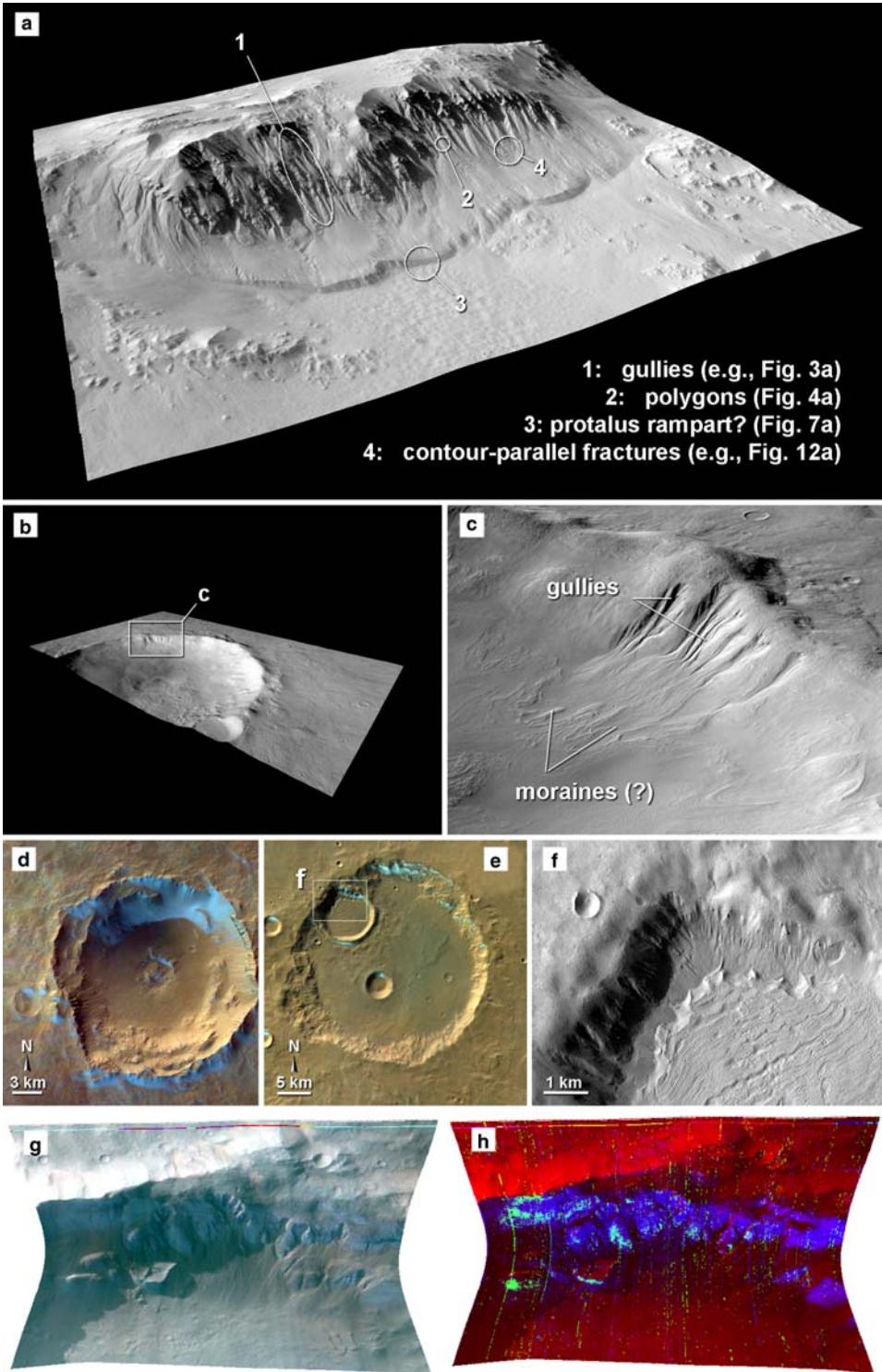


Fig. 14.

more temperate regions such as in NW Canada. In summary, it can be expected that it takes longer in a very cold and, presumably, rather dry climate on Mars to transform snow to firn and finally to ice than on Earth. This should be true even for recent periods of higher obliquity. Similarly, one might expect snowpacks on Mars to reach larger thicknesses than on Earth before they transform to glacier ice. Based on these qualitative considerations, it seems likely that in many cases the accumulation of snow did not result in a glacier, but in a thick snowpack with intercalated layers of dust and, perhaps, wind-blown sand (cf. Williams *et al.* 2008, fig. 3). The snow scenario is perfectly in agreement with an interpretation of the features shown in Figure 7a as proglacial ramparts because such landforms on Earth are evidence of snow accumulation. Sublimation of snow would, again, favour the formation of a lag deposit on top of the snowpack. The slow downward creep (Perron *et al.* 2003) in combination with compaction and sublimation of snow could induce fracturing of the overlying lag deposit (Fig. 12a). A terrestrial analogue for this process was described by Koster (1988), who investigated niveo-aeolian forms in Alaska. He found that denivation of sand-covered snow on dunes can produce deformational structures such as tensional cracks and compressional features (Fig. 12b) (see also Dijkmans 1990, fig. 3b), which are morphologically similar to the contour-parallel fractures and grabens commonly seen on the lower slopes of mantling deposits and fans on Mars (cf. Fig. 12a). The creep of the snowpack might also pile up some permafrost material at the base, analogous to the moraines in the dry and wet scenarios (Fig. 11c, stage II).

The melting of a dusty snowpack has long been recognized as a potential source of liquid water on Mars (Clow 1987), and more recent studies confirmed this possibility (Williams *et al.* 2008). While the results of Williams *et al.* (2008) apply only to periods of obliquity higher than that of today, Möhlmann (2010) emphasized the outcome of the ‘solid-state greenhouse effect’ in generating liquid water in snowpacks and concluded that, even in the current climate of Mars, liquid water can be produced. Williams *et al.* (2009) modelled snow melt at mid-latitudes on Mars and found that enough meltwater can be generated to produce gullies, an idea that had been previously suggested by Christensen (2003). Whenever the snow melting occurred exactly, it would be a viable process to provide the required liquid water for gully and fan formation in the ‘snow’ scenario. If an active layer existed in the past (Kreslavsky *et al.* 2008), solifluction might occur in the form of frost creep or gelifluction, although the period of the freeze–thaw cycles is difficult to constrain (day–night or seasonal cycles). Fractured mounds would form as erosional forms, not as pingos. Where all the snow in the surrounding has decreased in height or disappeared, snow hummocks would remain, consisting of residual snow patches or ridges (Koster & Dijkmans 1988). When the tops of these denivation forms are broken up into radial patterns, they display a strikingly similar morphology to Martian fractured mounds (Fig. 13). There is a huge difference in scale between the two types of fractured mounds shown in Figure 13, but the principle should work for the larger fractured mounds on Mars as well. The other landforms would form very similarly as in

Fig. 14. (Continued) Assemblages of possible periglacial landforms and water ice on Martian pole-facing crater walls. (a) Part of south-facing inner wall of Hale Crater, displaying several landforms that resemble periglacial landforms on Svalbard. CTX image P15_006756_1454 superposed on HRSC DEM (HRSC h0533_0000). View is towards the NE, no vertical exaggeration, image width is about 12 km. (b) Perspective view of a crater in the southern mid-latitudes (at 45.66°S, 238.11°E). CTX image B05_011519_1341 superposed on HRSC DEM (HRSC h0424_0000). View is towards the NE, no vertical exaggeration, crater diameter is 26 km. (c) Slightly rotated detail of the scene shown in (b), with gullies and possible moraines at the downward termination of the inferred location of former glaciers (view towards the north). (d) Snow and frost on pole-facing slopes (crater centre at 46.05°S, 183.85°E; detail of HRSC h8569_0000; image acquired during the southern winter at solar longitude (L_S) 147.8°). The bright material is likely to be water ice, as it was found by the Compact Reconnaissance Imaging Spectrometer (CRISM) at a similar latitude during the same season (see panels g and h). (e) Another example of snow and frost preferentially accumulated on pole-facing slopes (crater centre at 39.6°S, 158.32°E; detail of HRSC h8527_0000; image acquired during the southern winter at L_S 141.6°). The white box marks the location of panel (f) and corresponds to an area where bright material accumulated on the inner wall of a smaller impact crater. (f) Detail of the previous image. The area of snow accumulation corresponds exactly to sites where gullies, fans and moraine-like landforms are observed (detail of CTX B05_011746_1401). (g) CRISM false-colour image of a crater rim in Terra Sirenum (near 38.9°S, 195.9°E). Frost is characterized by a ‘bluer’ colour than the rock and soil. The image was taken during the Martian winter at L_S 140.6° (image source: NASA PlanetaryPhotojournal, #PIA09101). (h) Same scene as (g), with the colour indicating the depths of absorption bands of H₂O-frost at 1.50 μ m (blue) and CO₂-frost at 1.45 μ m (green). While CO₂-frost occurs only at the coldest, most shaded areas, water ice is more widespread and occurs on slopes incised by many gullies (image source: NASA PlanetaryPhotojournal, #PIA09101; see also Vincendon *et al.* 2009). Image credit: ESA/DLR/FUB, NASA/JPL/MSSS and NASA/JPI/JHUAPL.

the other scenarios (Fig. 11c, stage III). An important aspect of this scenario and the associated snow melting would be intensified chemical weathering, the role of which has been underestimated in the past even on Earth (Thorn 1988).

Conclusions

Despite significant differences in the climates of Mars and Svalbard, a suite of very analogous landforms has developed, although perhaps over enormously different timescales. Attempts to reconstruct palaeo-climates on Mars have to take into account the fact that different processes acting in different environments can produce similar results (equifinality). The integrated analysis of landscapes can reduce such ambiguities.

The landform inventory associated with pole-facing inner walls of impact craters in the Martian mid-latitudes (Fig. 14) suggests the geologically recent action and interaction of glacial and periglacial processes. Based on terrestrial analogue landforms in similarly close spatial proximity on Svalbard, three scenarios of sequential landscape evolution are presented for Mars. All scenarios start with initial snowfall and the deposition of a dusty snowpack, and they all end with recent gully and fan formation. These scenarios are qualitative in the sense that none of them is expected to exactly represent the real situation on Mars. In fact, the scenarios are not mutually exclusive, and mixed cases (e.g. the dry and the snow scenarios) are very plausible. Dependent on latitude and insolation, some craters might have been shaped by the dry scenario, while craters at other latitudes might have been shaped by the wet scenario. The different scenarios also have different implications for the interpretation of certain landforms. For example, fractured mounds are unlikely to be open-system pingos in the dry scenario because that does not predict liquid water in the subsurface, a prerequisite for the growth of hydraulic pingos. However, basal melting of snow in the snow scenario could lead to infiltration of liquid water into the subsurface and the formation of a hydraulic pingo as in the wet scenario.

The landscape evolution proposed here would be controlled by obliquity and/or orbital parameters such as eccentricity or the position of perihelion, and is therefore assumed to be cyclic. Several successive episodes of deposition and removal have already been suggested by, for example, Kreslavsky & Head (2002), Schon *et al.* (2009b) and Morgan *et al.* (2010). Processes implying an active layer might have operated in the past, although an active layer does not exist today (Kreslavsky *et al.* 2008). It is thus important to realize that the Martian

mid-latitude morphologies do not represent a stable situation over long periods. Instead, this is a dynamic landscape in constant, although perhaps very slow, transition, and patterns of sedimentation and erosion overprint each other repeatedly. Nevertheless, the associated rates for erosion (e.g. in the dry scenario) are likely to be very low, and not all traces of former ice ages are extinguished by later glaciations. Therefore, the spatial extent of former and more widespread glaciations can be identified by careful morphological analysis (Hauber *et al.* 2008; Dickson *et al.* 2008, 2010; Head *et al.* 2010).

Not all craters are necessarily expected to be exactly in the same stage of this landscape evolution. In general, however, the observations of gullies with very recent activity (e.g. Diniega *et al.* 2010; Dundas *et al.* 2010; Reiss *et al.* 2010) point to a late-stage situation for most mid-latitude craters at the present time. This is also in agreement with observations of current degradation of the mantling deposit in mid-latitudes (Mustard *et al.* 2001; Morgenstern *et al.* 2007; Lefort *et al.* 2009; Zanetti *et al.* 2010) and with theoretical modelling of ground-ice stability in the recent history of Mars (Chamberlain & Boynton 2007).

The importance of snow (Figs 12 & 13) should not be neglected in assessing the relative importance of glacial and periglacial processes on Mars. Snow and nivation processes are important factors in the geomorphology of polar and cold-climate regions (e.g. Thorn 1978; Christiansen 1998), and snowpacks might be viable alternatives to glacial interpretations of some Martian surface features. Wind should also be an important factor, as it can transport snow and accumulate it in protected regions (Head *et al.* 2008) where it could act as a landscape-forming agent.

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