CHAPTER 11

Lineated Valley Fill at the Martian Dichotomy Boundary: Nature and Degradation

Abstract

The escarpment of the Martian dichotomy boundary is a key region for the investigation of landforms related to creep of ice and debris comparable to terrestrial rock-glacier landforms of alpine and high-latitude periglacial environments. Although on Mars features termed as *lobate debris aprons, lineated valley fill* and *concentric crater fill* have been studied in detail since the late 1970s on the basis of Viking imagery (e.g., *Carr and Schaber*, 1977; *Squyres*, 1978, 1979; *Lucchitta*, 1984; *Squyres and Carr*, 1986), basic questions concerned with the composition as well as the style of emplacement and degradation still remain unanswered. This work focuses on lineated vally fill in a near-circular depression at the dichotomy escarpment in Deuteronilus Mensae. Analyses of a high-resolution Mars Orbiter Camera image mosaic suggest that such landforms have been formed early as the result of thermokarstic degradation of the southern highland terrain. Later, a much younger process related to the degradation of an ice-rich mantling deposit has led to formation of creep morphologies that might have been geologically active in the recent past. Morphological comparisons of *lineated valley fill* units with *concentric crater fill* landforms in Utopia Planitia strongly suggest comparable emplacement and degradation styles of both features and strengthen the theory that all these landforms, although different in shape and morphological expression, are basically identical and are formed under comparable initial conditions.

11.1. Introduction and Background

Landforms indicative of ice-assisted creep of debris at the highland-lowland boundary of the Martian *fretted terrain* comprise surface features generally known as *lineated valley fill (LVF)*, *lobate debris aprons (LDA)*, and *concentric crater fill (CCF)*. Common to these landforms are surface patterns, such as lineations, furrows, ridges, and alignment of pits, that are considered characteristic of the movement and degradation of mountain debris mixed with interstitial ice. These landforms are distributed along scarps and impact basins within the 40°-60°-latitude belts of both hemispheres suggesting a structural as well as a climatic control of their occurrence as shown in a considerable amount of studies (e.g., *Sharp*, 1973; *Carr and Schaber*, 1977; *Squyres*, 1978; *Lucchitta*, 1984; *Squyres and Carr*, 1986; *Mangold and Allemand*, 2001; *Chuang and Crown*, 2005b; *Li et al.*, 2005; *Head et al.*, 2006a; *Hauber et al.*, 2007). It is a commonly accepted that these landforms are prime Martian analogs of terrestrial rock glaciers or even debris-covered glacial systems (e.g., *Head et al.*, 2006a), and most observers agree that these landforms are indicators of past climatic conditions on Mars. It is also assumed that currently these landforms are undergoing degradation which supports the theory of recent changes of the climatic conditions on Mars. Such climatic changes

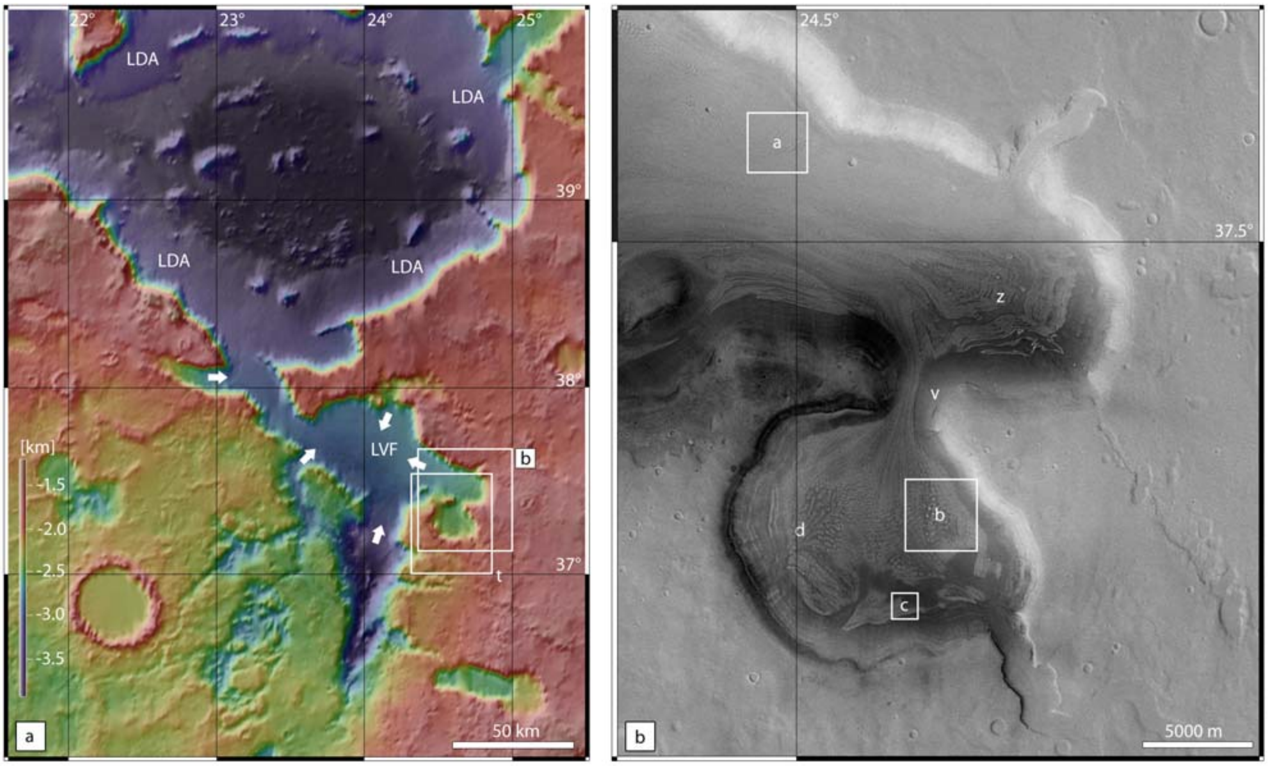

Figure 11.1.: Fretted terrain of the southern Deuteronilus Mensae area; [a] near-cirular depression (frames [t] and [b]) and adjacent valleys and depressions characterized by *lineated valley fill (LVF)* and *lobate debris aprons (LDA)*; frame [b] refers to figure 11.1b, frame [t] refers to the topographic profiles in figure 11.2a-b. Base map is a colour-coded MOLA MEGDR shaded relief superimposed on MOC-WA geodesy mosaic (see dark albedo); [b] nadir scene of HRSC orbit 1201_0000 showing details of depression infill; contorted low- and high-albedo pattern is suggestive of glacial surfaces ([z], see text for discussion). Intriguing dendritic pattern [d] and subparallel lineations at small outlet of the depression [v] are suggestive of debris transport in northern direction. Also note generally smooth appearance of walls and highland areas. Labeled boxes [a]-[c] refer to scenes displayed in figure 11.7.

might be connected to cyclic variations in the planet's orbital configuration (*Murray et al.*, 1973; *Toon et al.*, 1980) as recent modelling attempts and predictions suggest (e.g., *Laskar et al.*, 2004). Higher obliquities of the Martian spin axis might have caused a redistribution and deposition of polar volatiles in equatorial latitudes (*Forget et al.*, 2006) and, consequently, could be responsible for the formation of ice-related landforms at low latitudes. During lower obliquities the equatorial reservoir is depleted and volatiles are redeposited at higher latitudes again (*Levrard et al.*, 2004).

Robust predictions of spin-axis obliquities cover the last ~10-20 Ma but prior to this, solutions are non-unique due to the inherent chaotic nature of the obliquity variations. These uncertainties could be overcome or at least be stabilized, i.e., constrained, by observations of the geological inventory.

This work focusses on a *lineated valley fill* unit at the Martian dichotomy boundary which was deposited in a near-circular depression located south of Deuteronilus Mensae at 24.5°E, 37.25°N (figure 11.1a-b). The area can be considered as a key region for investigations on *lobate debris aprons* and *lineated valley fill* features and a considerable amount of work on the Deuteronilus area has been conducted so far by, e.g., *Squyres* (1978, 1979); *Carr* (2001); *Mangold and Allemand* (2001); *Kargel* (2004); *Head et al.* (2006b,a);

Table 11.1.: MOC-NA scenes used for generation of image mosaic covering the Deuteronilus Mensae depression. Values for Sun azimuths α_S have been corrected and are measured clockwise from north direction. Values listed refer to image label entries as given on the Malin Space Science Systems website (http://www.msss.com).

MOC	pixel scale [m/px]	longitude α [°E]	latitude λ [°N]	L_S [°]	acquisition yyyy-mm-dd	incidence i_S [°]	phase φ [°]	azimuth α_S [°]
E04-02217	4.66	24.33	37.70	14.50	2001-05-28	47.46	47.32	235.66
E05-01207	4.64	24.48	37.70	14.53	2001-06-13	50.64	50.60	232.78
E10-02835	6.48	24.13	37.87	13.59	2001-11-18	66.86	83.10	203.53
E11-03095	4.88	24.40	37.76	13.29	2001-12-19	63.42	80.11	200.06
R03-01488	3.23	24.35	37.74	14.61	2003-03-30	46.00	55.66	240.63
R04-00003	3.95	24.31	37.75	14.33	2003-04-01	43.52	69.91	235.89
R04-00308	3.24	24.29	37.84	14.63	2003-04-06	47.37	57.27	239.33
R04-00871	3.24	24.26	37.79	14.65	2003-04-13	48.70	58.78	238.16
R04-01511	3.24	24.22	37.81	14.66	2003-04-20	50.09	60.41	236.93
R05-01588	1.62	24.12	37.95	14.70	2003-05-19	55.80	67.01	231.83
R09-00936	3.24	24.54	37.75	14.07	2003-09-11	68.94	84.15	210.25
R16-00490	3.26	24.46	37.71	13.66	2004-04-07	38.46	52.33	222.42

Head et al. (2006).

11.2. Data and Methods

Images acquired by the MOC instrument usually offer detailed but limited insights into patterns discussed in this work because of the limited aereal extent of each MOC image. Very few locations, however, have been covered by MOC in a way that continuous mosaics can be created in order to study an area in detail and within a broader context. One of such areas is this particular depression located in Deuteronilus Mensae. Geomorphologic investigations presented in this work are predominantly based upon high resolution Mars Orbiter Camera (MOC) narrow angle images (NA) that have been processed individually and mosaicked to form an image mosaic with a pixel map scale of 5 m/px (figure 11.5). Twelve MOC raw images were processed using standard USGS/ISIS-2 routines up to level 2 (table 11.1) using identical map scales and reference system. For measurements, the mosaic was projected using a Lambert two-parallel projection centered at the image scene. Misalignments between individual MOC images caused by uncorrected external orientation data were corrected using manual rubbersheeting adjustments. Blank areas were filled with data obtained by the Mars Express High Resolution Stereo Camera (HRSC) in order to generate a geomorphologic map. Crater-size frequency analyses have been performed on the basis of MOC image data.

In addition to this, laser altimetry measurements from the Mars Orbiter Laser Altimeter (MOLA) were used in order to derive basic morphometric values for slopes and gradients. Except for overview maps where MOLA Mission Experiment Gridded Data Records (MEGDR) with a gridded map scale of 463 m/px have been used, more exact measurements were performed on cross-over corrected tracks from the MOLA Precision Experiment Data Records (PEDR). Raw datasets were made available through the Geosciences Node of the Planetary Data System (PDS) and the US Geological Survey (USGS).

11.3. General Settings

The *lineated valley fill* and the unusual depression (henceforth termed Deuteronilus Mensae depression) are situated in the *fretted terrain* of the Martian highland-lowland boundary. Stratigraphically the highland area is characterized as Hesperian-aged unit *Hr* composed of ridged plains material of volcanic origin that occurs throughout the highland areas (*Greeley and Guest*, 1987). Parts of the dissected areas are considered to represent mixtures of channel and mass wasting material (unit *Hch*). The depressions and fretted channels including the Deuteronilus Mensae depression are filled by Amazonian aged surficial material (unit *As*) which characterizes all major *lobate debris aprons* and *lineated valley fill* units at the dichotomy boundary. This unit is interpreted to be related to the creep of icy debris (*Greeley and Guest*, 1987).

The surrounding Hesperian-aged highland is situated on an elevation level of approximately -2500 m in the West and up to -1500 m in the East of the southern Deuteronilus area; floors of fretted channels are commonly located at an elevation level of -3000 m to -3500 m (figure 11.1a). Fretted-channel walls in the context area are characterized by large *lobate debris aprons* extending up to 20 km from adjacent escarpments towards the channel and depressions floors (figure 11.1a). Fretted channels and depression margins are characterized by relatively short V-shaped sapping valleys with short perpendicular tributaries incised into the highland terrain.

11.4. Characteristics and Morphology

The Deuteronilus Mensae depression on which this work is focussed has a slightly elliptical shape with an approximate diameter of 30 km in southeast-northwest direction and 20 km in southwest-northeast direction. The depression is incised into cratered and intact highland terrain. It has smoothly shaped walls sloping at an angle of approximately 15-20°. Footslopes are characterized by extensive talus deposits that extend up to several hundred meters downslope towards the center of the highland depression. Talus deposits extending in northern to northeastern directions are generally larger than tali extending in other directions. Deposits that have filled the Deuteronilus Mensae depression have an alternating high and low albedo texture and are aligned parallel and normal to slopes indicating direction of debris transport and suggesting flow or creep of debris material towards northern areas through a small and deeply incised 1-km gap in the north (v in figure 11.1b). While the southern part of the depression infill is located on an elevation level of -2450 m, the area north of the gap is on an elevation level of -2610 m resulting in a topographic gradient of ~0.5° as extracted from MOLA Precision Experiment Data Records (PEDR tracks) crossing the depression (figure 11.2). North of the gap, debris material merges with talus deposits from adjacent walls forming an contortion pattern as outlined by subparallel and bent dark and bright materials (figures 11.1b, 11.5 and 11.6).

The main units of the Deuteronilus Mensae depression infill can be separated by their albedo and textures: the first unit has a low relative albedo, is smoothly textured and shows several circular small-scaled depressions suggestive of impact craters. These impact craters have a diameter size of 10 m to 100 m, and have been used for crater-size frequency measurements in order to obtain model ages for the final stages of resurfacing events (figure 11.4). This relatively darker unit is predominantly located below rims and footslopes of the Deuteronilus Mensae depression, on the floor of a tributary valley in the southeast (figure 11.1b, figure 11.3f) and also near the central part of the depression where it is mixed with brighter material. The second unit has a higher relative albedo and a generally rough-textured appearance with parallel furrows, ridges and knob-like features that are either aligned or chaotically distributed across the surface (figures 11.3a-c). The relatively brighter material is almost exclusively located in the interior of the depression and shows lineations that are aligned in parallel to the main depression walls. The brighter material is also observed near the northern gap where lineations converge. North of the gap lineations diverge again and merge with surrounding slope units of darker material.

The interrelation between bright and dark units is characterized by areas where darker material truncates units of brighter material and also locations where the darker material overlays brighter units (figures 11.3a, b). At the talus zones, alternating bands of dark and bright material are observed (figures 11.5 and

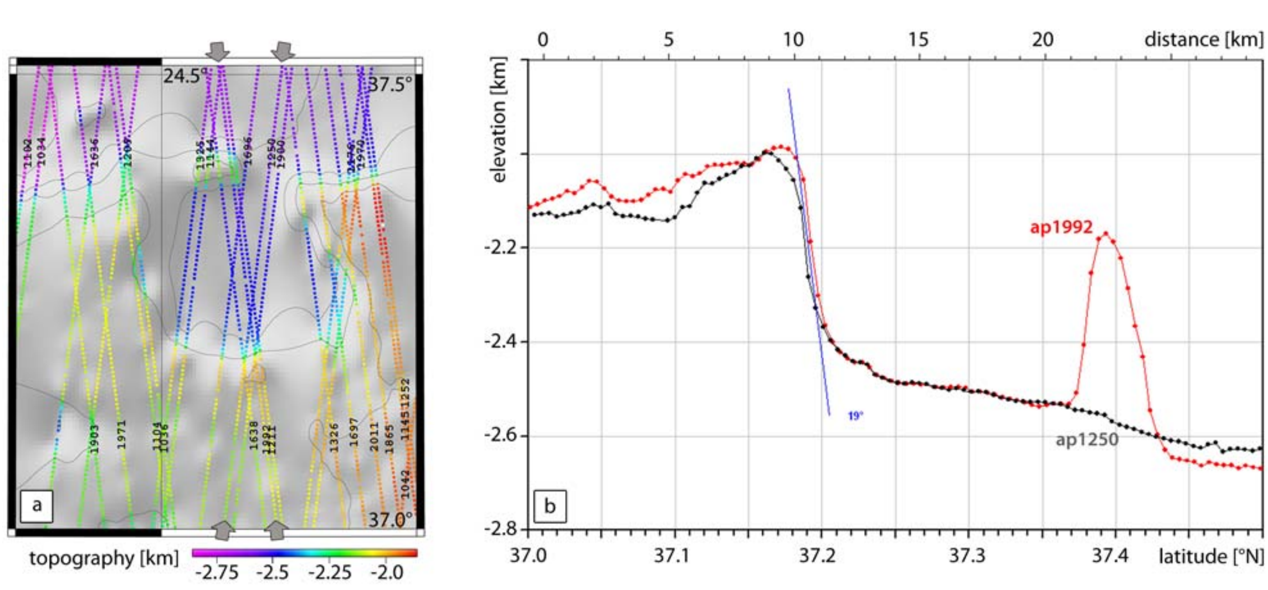

Figure 11.2.: Topography of the Deuteronilus Mensae depression; [a] colour-coded MOLA PEDR profiles superimposed on shaded relief map illuminated from 45°W and gridded with spacing of ~0.007 degree/pixel; [b] topographic profiles of PEDR tracks ap1992 and ap1250 as marked with arrows in figure 11.2[a].

11.6). Apart from bright and dark bands, zones with subparallel fractures are frequently observed (figures 11.3d-f). These structural features extend parallel to the main rim of the depression and are connected to talus deposits. Their general shape compares to glacial crevasses as they are arcuate, sub-parallel and partly displaced en-echelon. Along these cracks small pit chains are frequently observed.

At the eastern depression wall, overlapping MOC-NA scenes have been acquired during subsequent years. While the first image (E05/01207) taken in 2001 around autumn equinoxe (L_S=178°) shows a peculiar knob (figure 11.3d), the image taken in spring 2004 (R16/00490) is missing that particular feature (L_S=16°, figure 11.3e). The knob is circular in plan view and seems to form a cylindric body with a relatively flat top and a small central mould; the approximate diameter size is 40 m. The direction of the shadow which this knob casts towards the northeast is identical to the main direction of scene illumination (232.8° measured clockwise from the north), confirming that this observation is not caused by image artifacts. The shadow length is approximately 19 m (~ 4 px). The incidence angle was i = 50.6° during image acquisition, so the shadow length yields an approximate height of the feature of ~15 m. Other indicators for such changes in the area of the Deuteronilus Mensae depression could not be detected thus far.

11.5. Discussion

The morphologic depression in Deuteronilus Mensae is one among numerous other more or less elliptical closed depression features commonly observed at the Martian dichotomy boundary. Characteristic for most of these morphologic depressions is an infill composed of bright and dark lineated material with either a smooth or knobby surface texture. Subparallel lineations and contortion patterns as well as crevasses-like fracture patterns suggest debris flow and resemble terrestrial surfaces of valley glaciers. However, at closer inspection of the relationships between different surface units, many differences become apparent and there are several arguments against a glacial origin and development as it is generally known from terrestrial glacial systems.

The most obvious observation is that all of the surface is debris covered. For terrestrial valley glaciers and

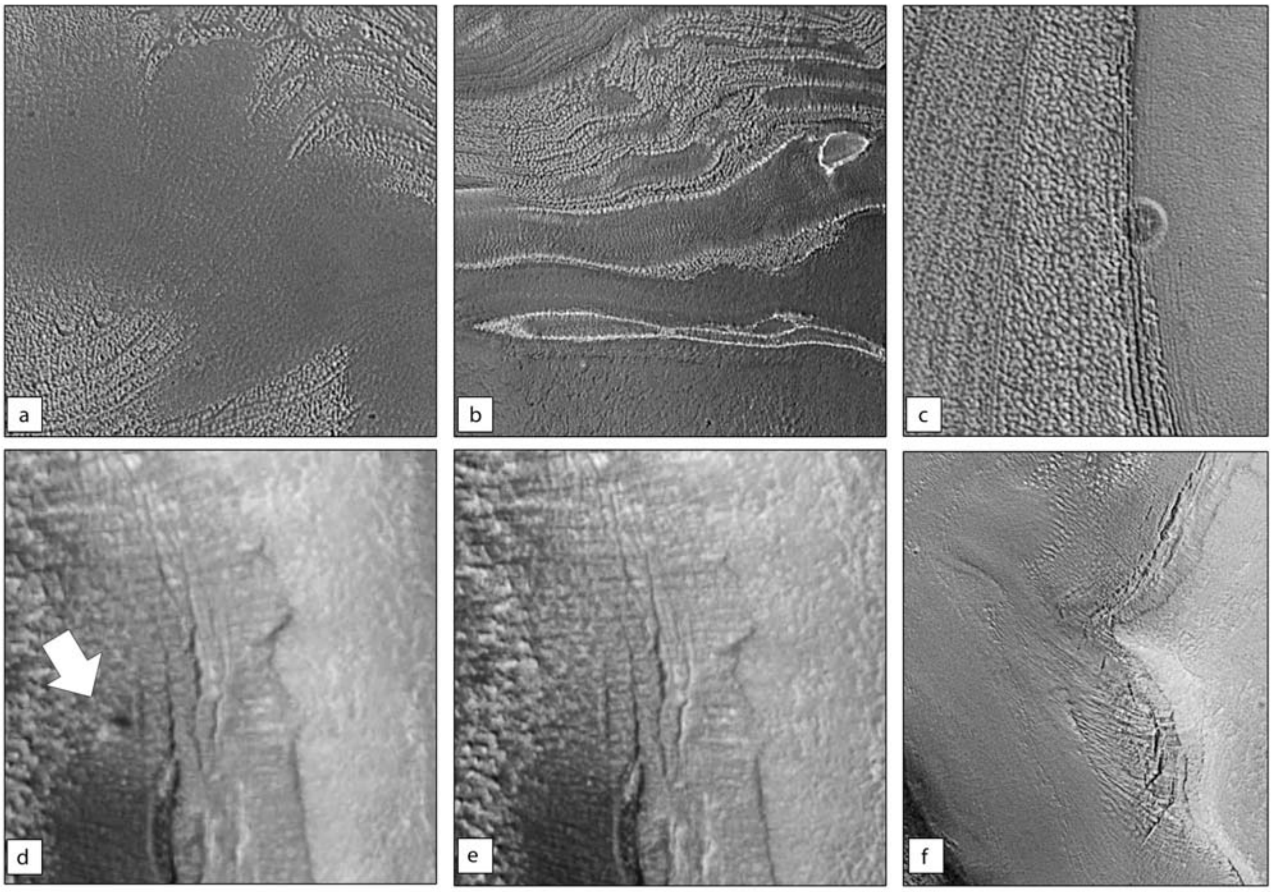

Figure 11.3.: MOC-NA image samples of the Deuteronilus Mensae depression, see figure 11.5 for scale and location; [a] arcuate lineations on bright material indicating direction of flow, dark material either truncates or superimposes bright deposits; [b] furrows and smooth elliptical depression indicating loss of material; [c] impact crater on footslope near small gap (v in figure 11.1b), bright material is superimposed on impact crater; [d] MOC scene E05/01207 and [e] R16/00490 showing a small knob (arrow) disappearing within 1.5 Martian years; [f] slope-parallel fractures indicative of slope movement and loss of material.

similar systems, steep wall-rock slopes are a prerequisite for providing debris to such a valley glacier's surface (e.g., *Benn and Evans*, 2003). Such steep slopes are absent in this area and there are no indicators for steady and considerable debris supply by rockfall or massive landsliding today. The degradation process therefore must be relatively old.

Although extensive talus deposits are observed at footslopes it remains questionable in what way this debris could have been deposited ontop of the surface of the debris-covered glacier in question. It seems plausible to assume that constant degradation of ice-rich wall-rock material in the past led to accumulation and mobilization of talus deposits which slowly moved downslope and merged in the center of the depression.

The occurrence of lineated debris material is limited to the interior of the circular depression and valley areas at lower elevation levels in the north. While valley glaciers on Earth are usually characterized by a distinct valley hierarchy and a high order of tributary valleys, such organization is not observed at the Deuteronilus Mensae depression. A broad valley cutting the depression walls in the south does not show any of these characteristic surface textures and can therefore not be considered as a tributary valley. On

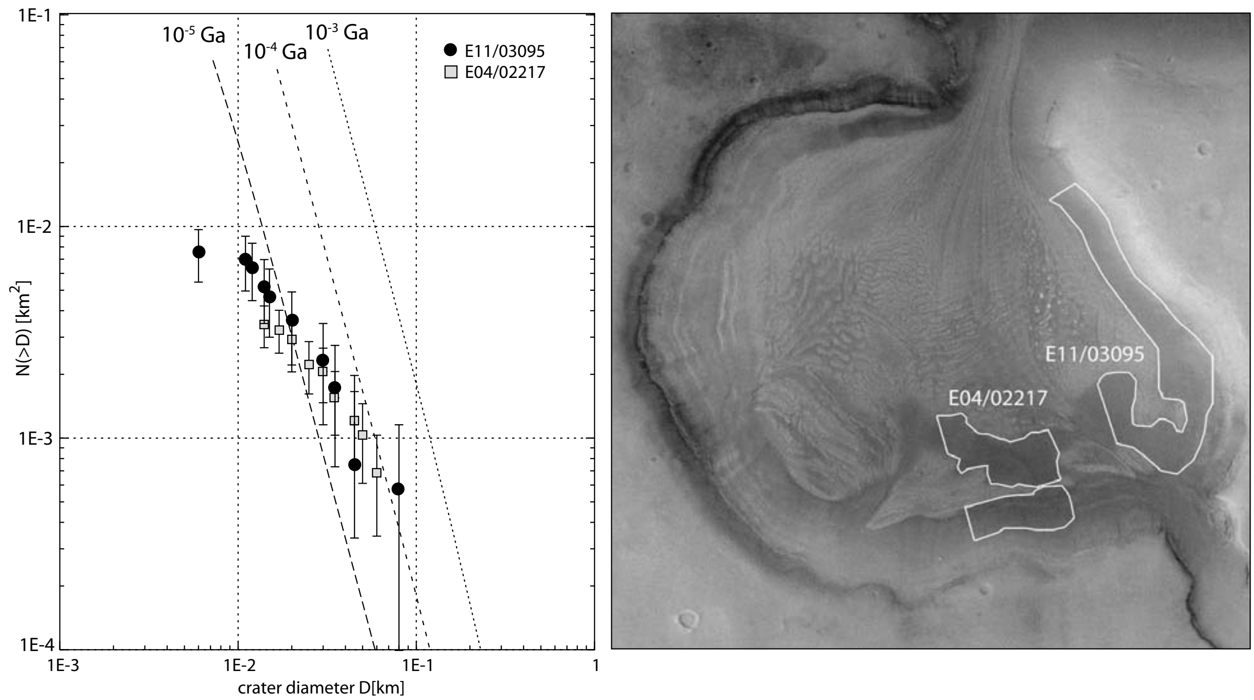

Figure 11.4.: [a] Crater-size frequency measurements for low-albedo material in the Deuteronilus Mensae depression. Isochrones plot based upon crater-chronology model by *Hartmann and Neukum* (2001) and production function coefficients by *Ivanov* (2001); model ages in the range of 10^{-5}-10^{-4} Ga imply near-recent activity; [b] HRSC nadir scence of orbit #1201_0000 acquired on 25 December 2004 with outlined mapping areas.

the basis of the available image data it remains hypothetical to assume that the depression forms a relic cirque feature as none of the diagnostic morphologies, such as three-sided steep cliffs are not observed.

It can, however, not be ruled out that there might be a body of relic solid ice buried by a thick debris cover acting as a lag deposit as suggested by, e.g., *Head et al.* (2006a), but the mechanism of ice accumulation still remains an open question. Some of the longitudinal striping and contortion patterns of dark material resemble closely medial moraines common for terrestrial valley glaciers, others are completely different as they transect brighter debris units or are buried by brighter deposits, There is no indicator for nonsteady flow in the upper part of the Deuteronilus Mensae depression which is characteristic of terrestrial glacial systems. The contortion pattern north of the small gap is mainly caused by the coalescence of debris material from the northern and eastern valley slopes with the material moving through the small gap. Contortion patterns are consequently controlled by the location of slopes and probably different slope angles. Furthermore, it would be unusual for a glacial system if the alleged moraines simply cross and truncate glacial units, as observed, e.g., in figure 11.3a. Additionally, elliptical-shaped features with a central elongated depression, as displayed in figure 11.3b, are difficult to explain by glaciers, espacially when compared to systems found on Earth.

In the western part of the Deuteronilus Mensae depression, an unusual dendritic pattern and isolated elliptically shaped patches of bright materials are visible that also cannot be explained if we consider glacial flow and formation of moraines (figures 11.5 and 11.6). The dark material is partly superimposed on brighter units (figure 11.3a) and partly buried by the bright units as seen in figure 11.3c and in context in figure 11.5, box [c]. This indicates that slope formation

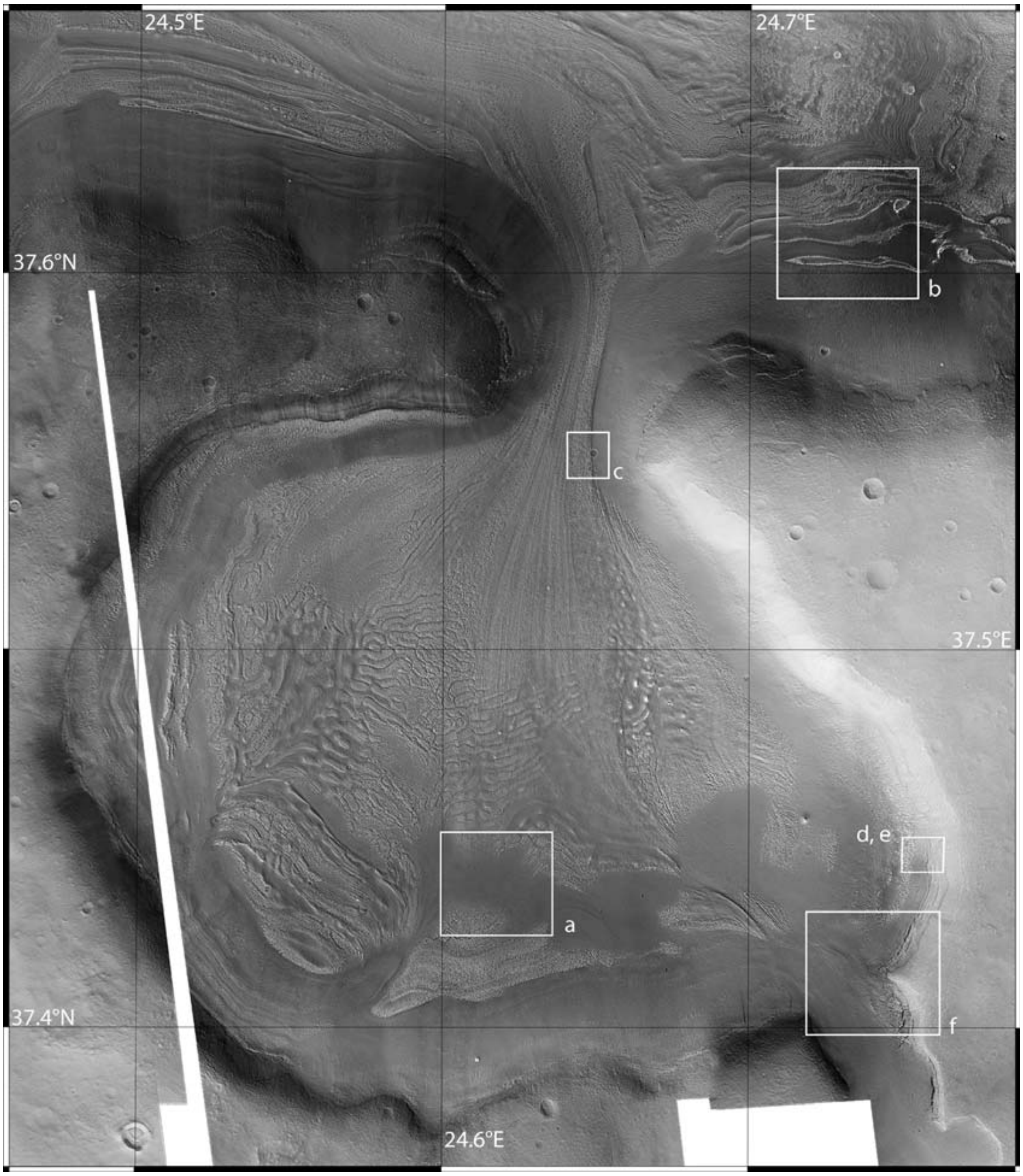

Figure 11.5.: MOC-NA image mosaic (5 m/px) covering the Deuteronilus Mensae depression in the Martian fretted terrain; labelled boxes refer to MOC samples in figure 11.3; for MOC-NA scenes used, see table 11.1.

and talus production initiated before accumulation of bright material and was ongoing contemporaneously to accumulation and downslope movement. Additional debris was spread over existing bright material and was probably also windblown to locations where the texture of the bright material is still faintly visible (figure 11.3a). On the basis of these observations, a direct comparison to morphologies on Earth can not be established. Apart from the general context and assembly of various surface units, the structural inventory needs further discussions. Small pits with an elliptical to circular shape as often observed in the study area are usually associated to removal of material from the subsurface resulting in collapse structures. Such pits and holes of non-impact origin suggest that processes such as sublimation might have

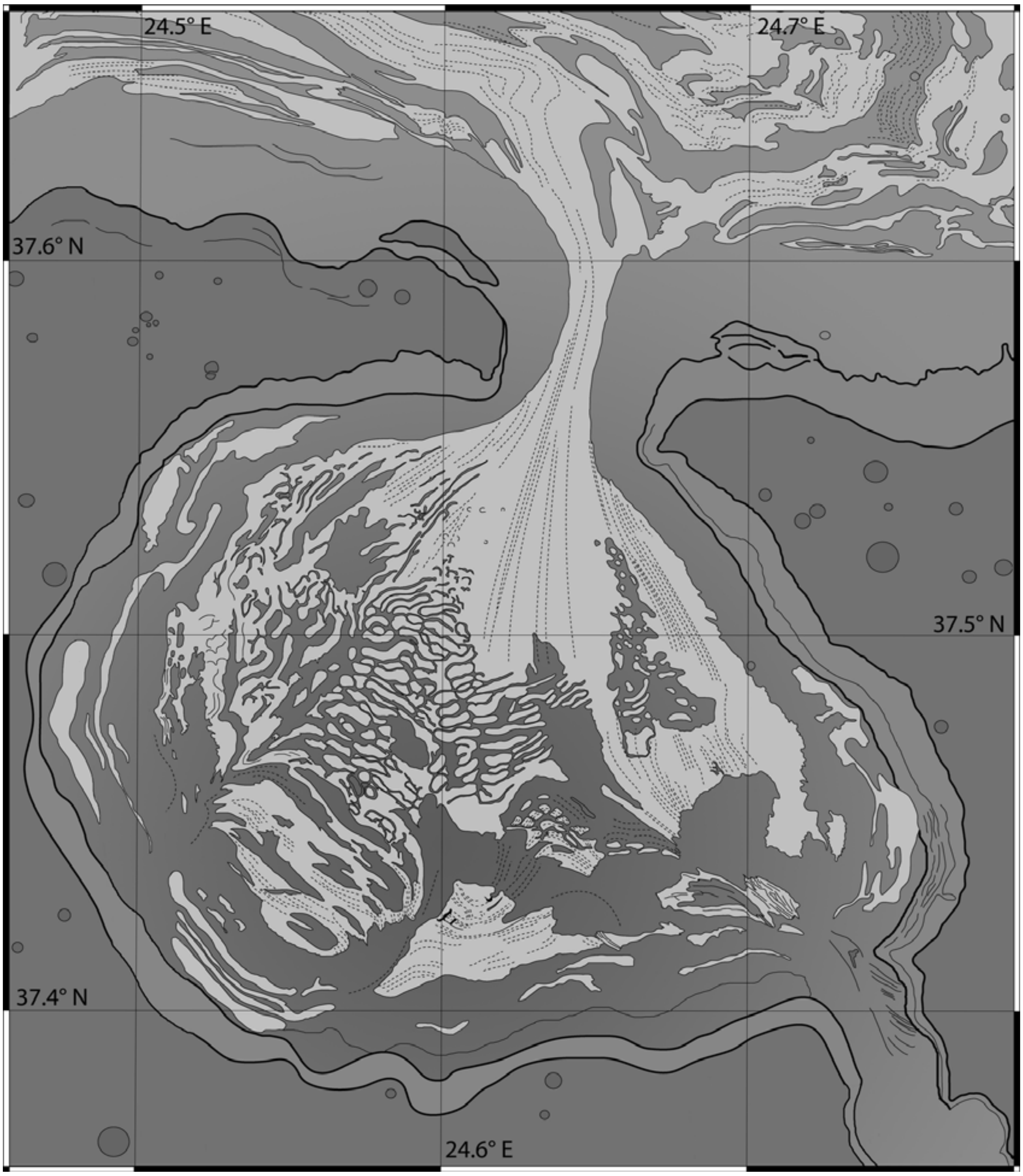

Figure 11.6.: Geomorphic map of surface and albedo units as mosaicked in figure 11.5. Flow pattern and alternating striping is suggestive of flow towards north through a narrow gap. Debris material was contributed from a small valley in the southeast and from footslopes; Bright gray units represent higher-albedo debris material (figure 11.5); dotted lines indicate flow lines, filled circles are impact craters. Blank areas in figure 11.5 were filled with HRSC image data.

played a significant role during the development of the debris-transport system. A possible explanation for their origin are depressions which can be found on some terrestrial glacial bodies that are subject to degradation. The process involved in this degradation is termed *glacial karst* and is an indicator for stagnation and disintegration of the glacier/debris body (e.g., *Menzies*, 2002). For the pits and pit chains observed at the Deuteronilus Mensae depression sublimation of water-ice or even carbon-dioxide ice could be a possible explanation for both removal of ice from ice-rich debris or from a body of solid ice covered by the debris. Either thinning of the debris cover or changes in the climatic environment, i.e., intensity of insolation, might have been responsible for the loss of subsurface ice. It seems, however, likely that pits associated with talus slopes are formed during the movement of slope deposits and the formation of tensional fractures.

Structures roughly resembling glacial crevasses as seen in figures 11.3d-f are usually associated with pits distributed along these fractures suggesting that processes leading to their formation, e.g., sublimation, are also responsible for the formation of fractures. Crevasses usually form as a result of extensional stresses in glacial systems and display gradient changes in the subsurface topography. On a footslope, extensional forces are quite unusual as wall-rock material accumulates and produces lobate features more akin to overthrusting faults as seen on, e.g., talus-derived rock glaciers. Instead, these features observed here, point towards phases of abrupt movement of talus material. When the internal friction and cohesion is exceeded by gravitational forces, material instantaneously moves downslope and stabilizes at a location where the gravitational forces are lower than the internal friction. Such movement occurs if material gets saturated with, e.g., water or snow (e.g., *Selby*, 1982). It is imaginable that such a formation of fissures and cracks leads to release of volatiles and ice that was initially stabilized under a protective cover of debris ultimately resulting in formation of pits and pits chains or even larger thermokarstic depressions.

The deposits in the Deuteronilus Mensae depression compare closely to what is observed in connection to the so-called *concentric crater fill* (*Squyres*, 1978) at other locations on Mars. When textural and morphological observations are compared (figure 11.7a-c), it becomes obvious that they seem to form identical types of deposits. These units are interpreted as degradation features of an ice-rich mantling deposit found globally at mid-latitudes of Mars (e.g., *Milliken et al.*, 2003). It is therefore assumed as already anticipated by, e.g., *Squyres* (1978) that although the different terms *concentric crater fill* and *lineated valley fill* are related to the general morphological context in which the features occur, the formation of both landforms is essentially identical. If the uppermost layer in the Deuteronilus Mensae depression is an ice-rich mantling deposit, flow or creep and formation of pits and cracks is most probably connected to this deposit and not to a body of ice underneath that deposit. Therefore, the mantling deposit is not related to the formation of the Deuteronilus Mensae depression.

Consequently, two major processes have taken place: [1] thermokarstic degradation of the ice-rich highland terrain and transport of debris mixed with ice towards the north and [2] deposition of an ice-rich mantling deposit which is undergoing more or less recent modifications (*Morgenstern et al.*, 2007). Whether the mantling deposit covers older ice-rich deposits protecting it from further disintegration or whether all ice has been removed before the mantling deposition took place cannot be determined. Therefore, it remains an open question whether the creep deformation we observe is related to the uppermost mantling deposit or also to the deposit underneath that cover.

Young ages far below 1 Ma as derived from crater-size frequency measurements, essentially no impact craters on talus deposits as well as seasonal changes on the surface suggest geologically recent activity. The nature of the cylindrical feature which disappeared in the course of 1.5 Martian years is not known but a non-aeolian origin seems likely as the geometry is not comparable to what has been observed for, e.g., Martian dust-devils (*Stanzel et al.*, 2006; *Greeley et al.*, 2006).

Whether the debris-transport system is still active today remains questionable as no other surface changes have been observed in that area. However, rates of change might be too small to be detected in multiple observations with MOC images.

Seasonal changes, as observed in figures 11.3d-e, are consistent with the very young ages derived from crater-size frequency measurements. Although the results should be treated with care, with ages younger than 100 ka, they clearly indicate that resurfacing occurred in geologically recent times. Although the large size of the intriguing cylindrical feature and the

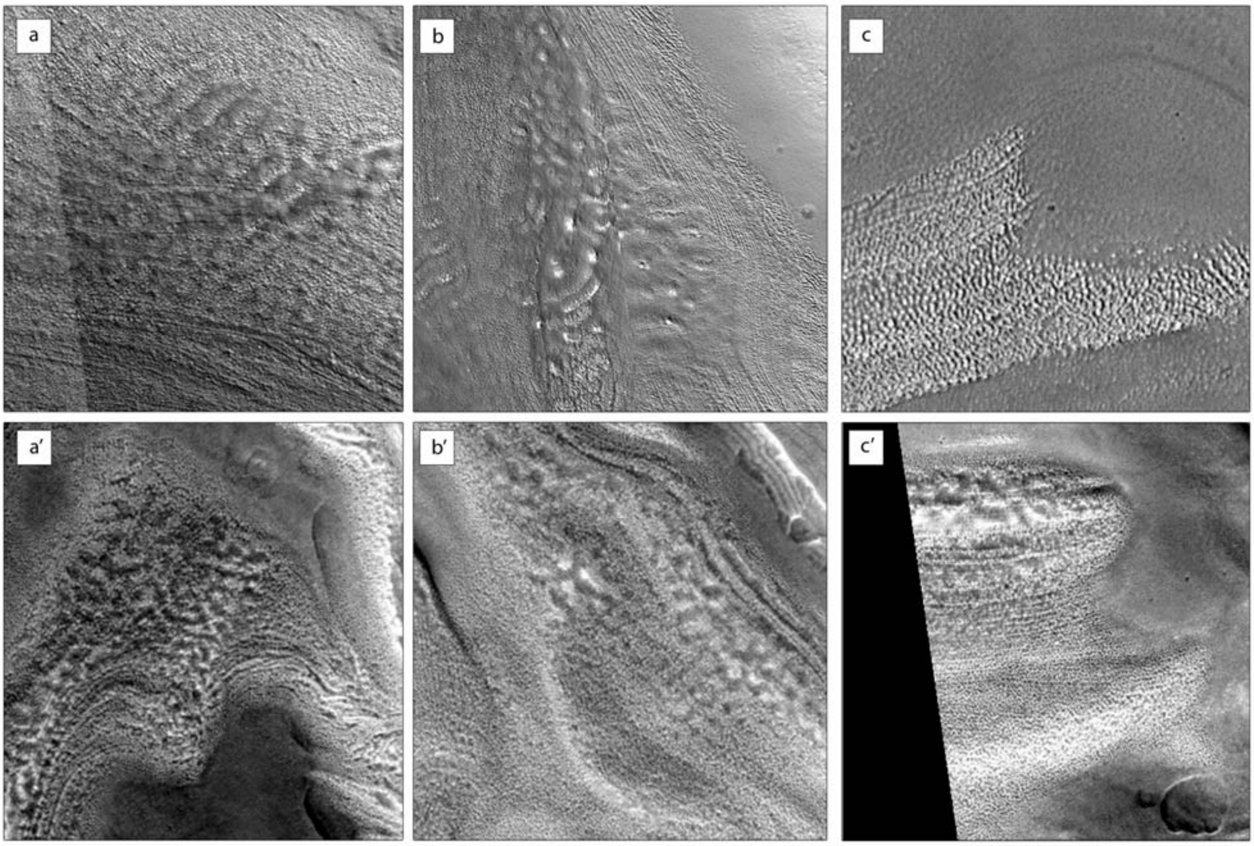

Figure 11.7.: Comparison of MOC scenes covering Deuteronilus Mensae and typical impact craters in Utopia Planitia; [a-c] refer to image scenes depicting the Deuteronilus Mensae depression, [a'-c'] refer to MOC scenes covering impact craters in Utopia Planitia. [a-a'] degradation texture, location of the Deuteronilus scene is slightly north of the image extent as displayed in figure 11.5 (see figure 11.1b for location), image scene in [a] is 6 km across, scene in [a'] is 3.3 km across; MOC scene for Utopia Planitia is E16-00342 located 43.6°N, 82.8°E. [b-b'] flow lines and degradation texture (see figure 11.1b for location), Utopia Planitia impact crater in [b'] is covered by MOC scene R15-02691 located 44.2°N, 81.9°E, scenes are 3 km across. [c-c'] remnant knobby surface, partly covered by lower-albedo material, Utopia Planitia impact crater in [c'] is located near 43.6°N, 83.6°E and is covered by MOC scene R14-00605 (see figure 11.1b), scenes are 3 km across.

shadow it produces as well as similar illumination conditions in all MOC scenes confirm that it is not an image artifact, its possible nature remains puzzling.

Two scenarios are imaginable, first, this feature occurs and disappears in a seasonal context, i.e., it depends on seasonal variations, or, secondly, this feature disappeared at some time after imaging in 2001. Whatever the true nature and the story behind its disappearance, it has not left any marks on the surface as far as it can be seen in 11.3e. It is. however, most probably not connected to slope processes as we would expect to see, e.g., widening of fractures or other indicators for downslope movement in the vicinity or at any other location in the area.

If this feature is related to aeolian activity, other areas in that region should also be affected causing very young ages. If not, this feature is one of the very few observations on Mars, that document active geological processes at the solid surface that have - thus far - only been reported from slope streaks, impact crater observations or from surface changes at the south polar cap (e.g., *Thomas et al.*, 2000; *McEwen et al.*, 2003;

van Gasselt et al., 2005).

11.6. Conclusions

Our observations at the location of the Deuteronilus Mensae depression point towards two major land-forming processes: Massive degradation of subsurface ice (permafrost) is followed by a more recent deposition of an ice-rich atmospherical deposit at Martian mid-latitudes which is currently subject to degradation. Formation of the Deuteronilus Mensae depression and of numerous quite similar intra-highland depressions in the fretted terrain as observed by (*Carr*, 2001) is probably connected to the removal of subsurface volatiles and subsequent collapse of the surface. Subsurface ice that is being removed either by sublimation or by melting and which is mixed with wall-rock debris has been discussed for the fretted terrain at the Martian dichotomy (*Squyres*, 1978, 1979; *Lucchitta*, 1984; *Carr*, 2001; *Mangold and Allemand*, 2001; *Kargel*, 2004; *Head et al.*, 2006b,a; *Head et al.*, 2006) as well as from southern hemispheric impact basins (*Squyres*, 1978, 1979; *Crown and Greeley*, 1993; *Chuang and Crown*, 2005b). For the location in Deuteronilus Mensae the following scenario is proposed:
(a) An older effect caused by thermokarstic degradation of ground-ice-rich material results in subsidence and collapse of depressions as also suggested, e.g., by *Carr* (2001). Most of the ice was present in the subsurface and was located under a protective cover of regolith and debris material. The mobilization of ice in combination with eroded wall-rock debris caused landforms indicative of creep and flow as commonly observed at the Martian dichotomy boundary. The process leading to melting of ice is still unknown but it seems reasonable to assume that it is related to changes of the orbital configuration of Mars as suggested by, e.g., *Mellon and Jakosky* (1995); *Laskar et al.* (2004).

(b) Phenomena and morphologies related to creep deformation which we observe at the Deuteronilus Mensae depression cannot be compared to typical (debris-covered) glacial surfaces on Earth. It is more likely a debris transport system with considerable amounts of interstitial and pore ice. The degradation of this material has resulted in landforms that are undistinguishable from the degradation of a young mantling deposit in Utopia Planitia (*Morgenstern et al.*, 2007) (figures 11.7). This volatile-rich mantling deposit forms the uppermost and youngest surface which is superimposed on morphologies formed by thermokarst degradation processes described in (a). The resemblance to other landforms, e.g., concentric crater fill in Utopia Planitia, suggests that the process is not a local phenomenon but that it is rather related to climatic conditions on a global scale.

Different creep morphologies as observed today cannot be unambiguously attributed to either the old process of mass-wasting as a consequence of thermokarstic degradation or to deformation of the young mantling deposit. It is imaginable that both units are mixed and form landform morphologies that have no counterpart in terrestrial environments. □