CHAPTER 12

GEOMORPHIC EVIDENCE FOR FORMER LOBATE DEBRIS APRONS AT LOW LATITUDES ON MARS: INDICATORS OF THE MARTIAN PALEOCLIMATE

Abstract

Circumferential depressions enclosing mesas and plateaus in the northern Kasei Valles and in the Tartarus Colles regions of Mars are interpreted as indicators of the former extent of lobate debris aprons, thought to be mixtures of ice and clastic particles. These former lobate debris aprons existed about 1 Ga ago and were embayed by lavas or other flow deposits. After the lobate debris aprons had been removed by sublimation and deflation, topographic depressions with a depth of 50 meters and a width of several kilometers were left behind between the mesa or plateau scarp and the solidified flow materials. These depressions or moats are located equatorwards of ±30° at significantly lower latitudes than generally observed for occurrences of modern, intact lobate debris aprons. This observation provides evidence that the paleoclimate at that time was different than today, probably due to a higher averaged obliquity of the planet's rotational axis.

12.1. Introduction and Background

Lobate debris aprons (LDA) are distinctive geomorphic landforms showing possible evidence for the creep and deformation of ice-rich debris in Martian mid-latitudes (e.g., *Carr and Schaber*, 1977; *Squyres*, 1978, 1979; *Lucchitta*, 1984). They occur predominantly at and near the northern hemispheric dichotomy escarpment and at margins of the southern hemispheric impact basins of Mars. LDA typically extend for up to 20 km from mesas or plateau scarps and show distinct flow lobes in plan view and convex-upward profiles in cross section with steep termini (*Mangold and Allemand*, 2001; *Pierce and Crown*, 2003; *Li et al.*, 2005; *Chuang and Crown*, 2005b; *Crown et al.*, 2006). Where LDA are confined in broad and narrow valleys, they are termed lineated valley fill and show a particular surface texture characterized by generally valley-parallel lineations (e.g., *Kress et al.*, 2006; *Head et al.*, 2006a,b). A third type of landform which is genetically connected to creep of ice and debris is termed concentric crater fill and is characterized by creep of material downwards along the inner slopes of impact craters.

LDA were first described in detail by *Carr and Schaber* (1977) and *Squyres* (1978, 1979), who ascribed them to downslope transport of erosional debris mixed with ice, analogous to terrestrial rock glaciers (e.g., *Wahrhaftig and Cox*, 1959; *Barsch*, 1996; *Whalley and Azizi*, 2003). *Squyres* (1979) and *Squyres and Carr* (1986) mapped the global distribution of LDA and found a strong concentration in two latitudinal bands with a width of 25°, centered at 40°N and 45°S. They concluded that this latitudinal dependence im-

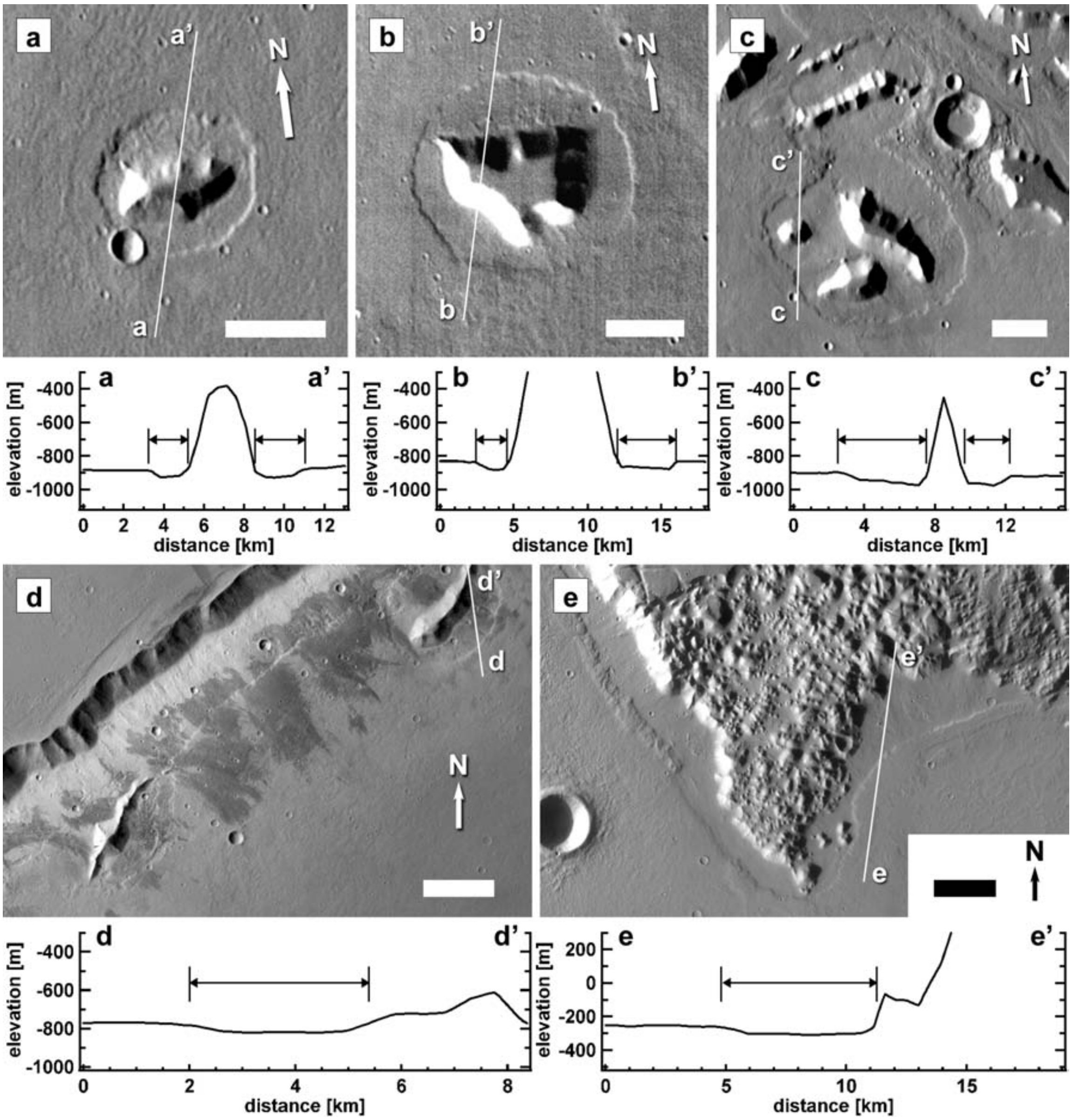

Figure 12.1.: Topographic depressions around mesas [a-c] and along the base of linear topographic scarps [d,e] in the northern Kasei Valles region. The outlines of these moats, as seen in plan view, are identical to those of modern lobate debris aprons, which are thought to be mixtures of ice and rock or dust particles (e.g., *Squyres*, 1978). (a) THEMIS-IR I03610002, at 30.12°N and 288.90°E. (b) THEMIS-IR I17414012, at 29.85°N and 288.25°E. (c) THEMIS-IR I04746014, at 29.85°E and 289.79°E. (d) HRSC 3217, at 29.03°N and 285.97°E. (e) mosaic of THEMIS-VIS images V13533007, V11686007, and V17826031, at 25.2°N and 282.71°E. Topographic profiles from MOLA data are given for each scene, and the widths of the moats are indicated by arrows. The depth of the moats are relatively uniform and range between 40 m and 50 m. Scale bar for all images is 5 km. An overview of the exact locations is given in figure 12.5.

plies a climatic influence on the formation of lobate debris aprons. Beside these macro-scale landforms, a concentration of small-scale viscous flow features in the same latitudinal belts was later observed by *Milliken et al.* (2003) on high-resolution Mars Orbiter Camera (MOC) data. Virtually no viscous flow features were reported equatorwards of ±30°, although possible glacial landforms were reported from tropi-

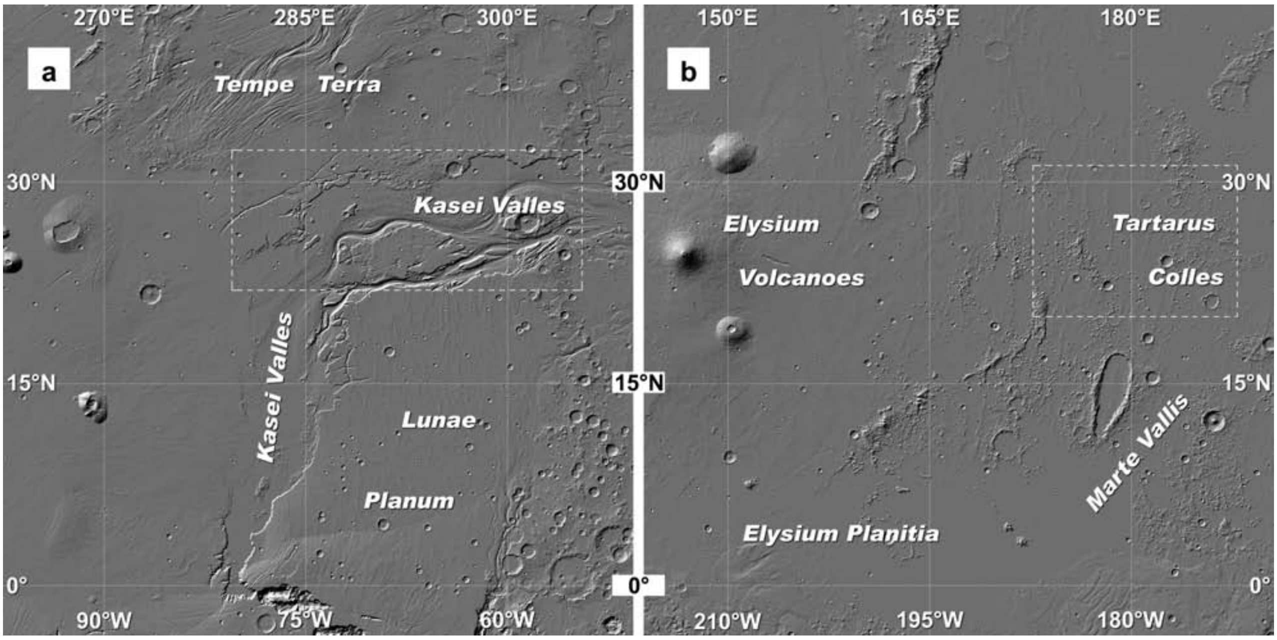

Figure 12.2.: Location maps of study areas. (a) Kasei Valles region with study area (see figure 5) marked by dashed white outline. (b) Tartarus Colles region east of the Elysium bulge, with locations of former lobate debris aprons approximately outlined by dashed white line. Background map is a shaded version of gridded MOLA topography.

cal regions on Mars. These are mainly located westwards of the Tharsis Montes and Olympus Mons (e.g., *Lucchitta*, 1981; *Head and Marchant*, 2003; *Head et al.*, 2005; *Shean et al.*, 2005a; *Milkovich et al.*, 2006; *Shean et al.*, 2007), and are morphologically distinct from LDA. They seem rather to be the result of orographically induced accumulation of ice (*Forget et al.*, 2006) and are not wide-spread phenomena like LDA. It has been shown first by *Squyres* (1978) on the basis of photoclinometry and later by *Mangold and Allemand* (2001) as well as *Li et al.* (2005) on the basis of MOLA topographic profiles that the cross-section shape of LDA can be approximated by the flow law of polycrystalline ice (*Glen*, 1953) and the flow relation of ice (*Vialov*, 1958) as done by *Paterson* (2001) for terrestrial ice sheets. *Colaprete and Jakosky* (1998) modelled flow of ice under Martian conditions and found that (a) temperatures 20 to 40 K higher than present average mid-latitude temperatures (~210 K), (b) ice contents ≤80%, and (c) net accumulation rates of ≤1 cm a^{-1} are required to create LDA of the observed size.

Ice in LDA may have several origins. Water ice could form by direct condensation of ice from the atmosphere (*Squyres*, 1978) or by snow precipitation (*Squyres*, 1989; *Head et al.*, 2006a). It could also accumulate by water vapor diffusion down into the regolith and subsequent condensation (*Mellon and Jakosky*, 1995) or by seepage of groundwater into debris and the creation of interstitial ice (*Squyres*, 1989). The clastic particles in the LDA might come from rock falls and talus deposits that accumulated at the base of scarps (*Squyres*, 1978; *Colaprete and Jakosky*, 1998) or, alternatively, from landslides (*Lucchitta*, 1984; *Mangold and Allemand*, 2001; *Pierce and Crown*, 2003).

LDA are young landforms. Crater counts yielded low crater densities, and absolute ages of a few 100 Ma or less have been derived (e.g., *Squyres*, 1978; *Mangold*, 2003; *Berman et al.*, 2003; *Head et al.*, 2005; *Li et al.*, 2005; *van Gasselt et al.*, 2007).

In this study, we analyze unusual moats around mesas and along topographic scarps which resemble the shapes of lobate debris aprons in plan view, using image data (MOC, THEMIS, HRSC) and PEDR (Precision Data Experiment Record) MOLA topographic profiles (figures 12.1 and 12.2). We present morphological evidence for the existence of former LDA,

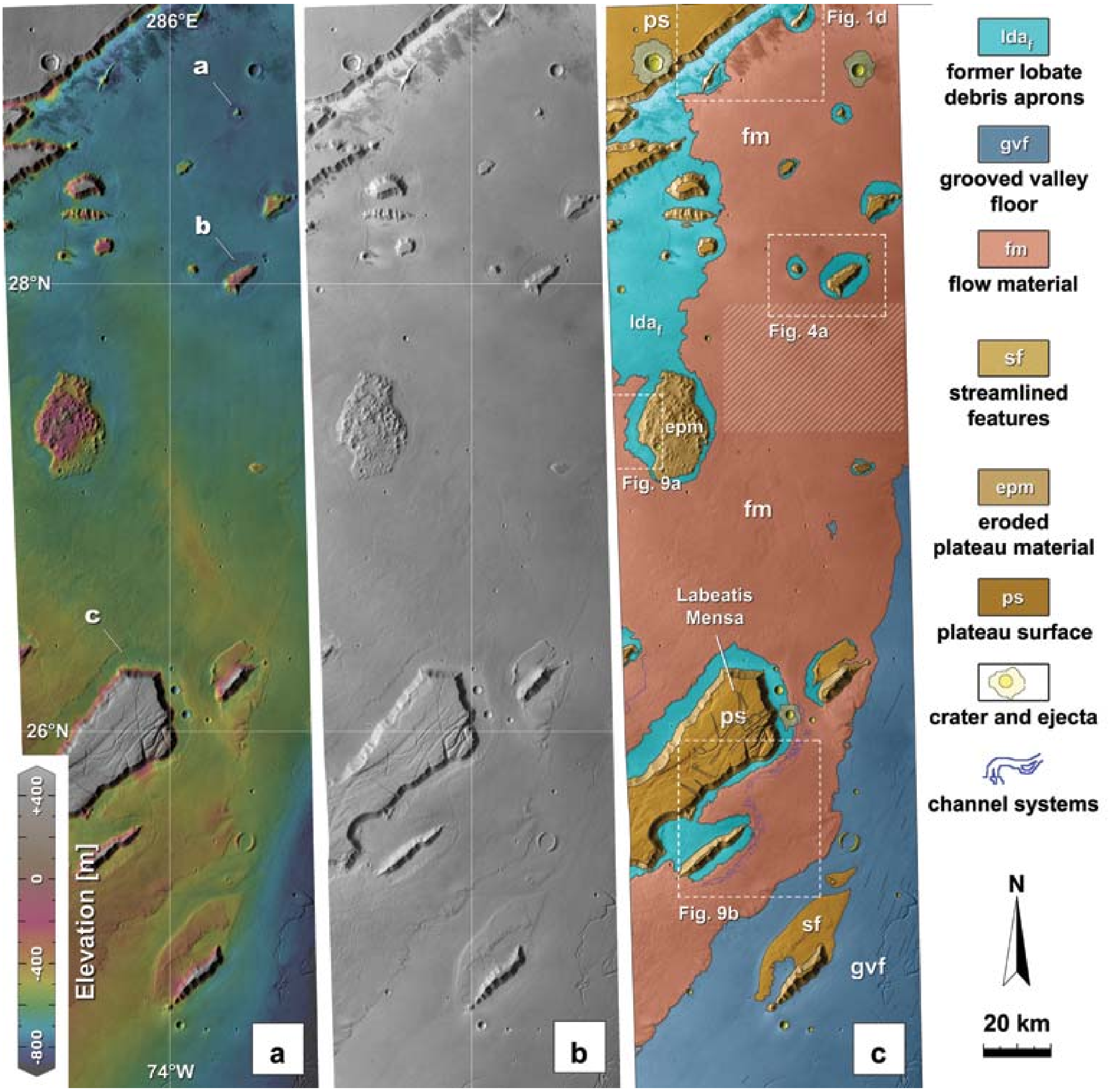

Figure 12.3.: Detailed maps of a part of the study area in sinusoidal projection. (a) MOLA topography superimposed on HRSC nadir channel of orbit 3217. Labels (a-c) mark examples of topographic depressions enclosing mesas. (b) HRSC nadir scene of orbit 3217. (c) Geomorphologic sketch map, aided by the maps of *Chapman et al.* (1991) and *Rotto and Tanaka* (1995). The moats (unit *ldaf*) enclose mesas and follow the base of plateau-bounding scarps. Both mesas and plateaus (units *ps* and *epm*, respectively) consist of Hesperian ridged plains material as mapped by *Rotto and Tanaka* (1995). The moats are embayed by lava flows or lahars (unit *fm*; corresponding to unit *At4* of *Rotto and Tanaka* (1995)), which cover the grooved floor of Kasei Valles (unit *gvf*; corresponding to unit *Hchv* of *Rotto and Tanaka* (1995)). Faint channel systems can be observed near some of the depressions. Base map is part of HRSC image 3217. Boxes with dashed white lines mark locations of figures 12.2d, 12.4a, and 12.9; dashed area marks location of crater counts (see figure 12.8).

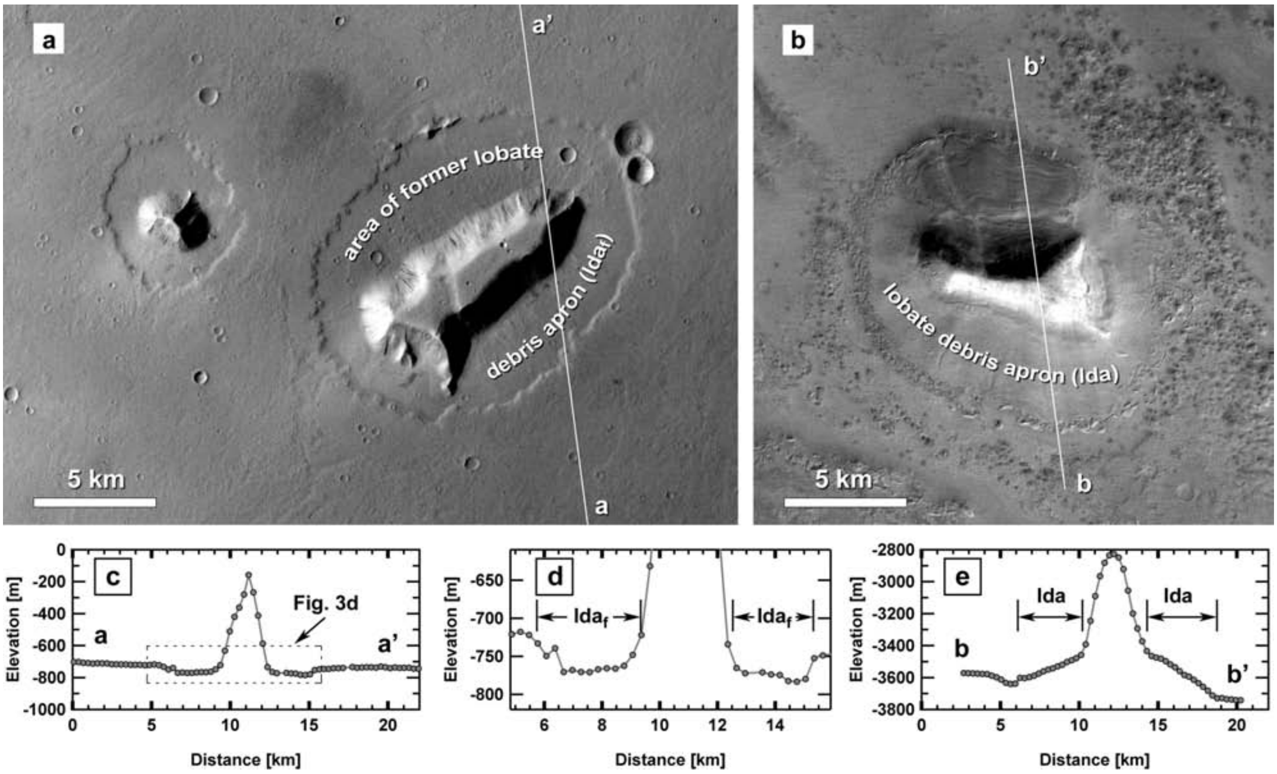

Figure 12.4.: Comparison between area of former lobate debris apron and modern lobate debris apron. (a) Two moats around mesas in the northern Kasei Valles region at 28.07°N and 286.25°E (detail of HRSC image 3217; see figures 12.3 and 12.5 for exact location). (b) Modern lobate debris apron in Deuteronilus Mensae (mesa centered at 46.29°N, 26.6°E; detail of HRSC image 1461). (c) Single topographic MOLA PEDR profile (track 15483) across area of former LDA, location is marked a-a' in figure 12.4a. (d) Detail of topographic profile a-a', showing the depth of the depression and its almost flat floor. (e) Single topographic MOLA PEDR profile (track 10306) across modern and intact LDA, location is marked b-b' in figure 12.4b.

which emplaced equatorwards of 30°N more than 1 Ga ago, and draw conclusions for the paleoclimate at that time.

12.2. Geologic Settings

The main focus of our study is on topographic depressions, henceforth called moats, which enclose mesas or are parallel to steep topographic scarps (figure 12.1). These moats are located in northern Kasei Valles, the largest outflow channel on Mars (e.g., *Baker and Kochel*, 1979).

The study area was geologically mapped at global scale by *Scott and Tanaka* (1986), at regional scale by *Rotto and Tanaka* (1995), and partly at local scale by *Chapman et al.* (1991). Moats occur on a flat-lying terrace, which is situated north of Kasei Valles' main channels and south of the Hesperian ridged plains of Tempe Terra. The surface of the western part of this terrace was mapped as Amazonian-aged lava flows associated with Tharsis volcanism (unit *At4*), while the eastern part was interpreted as eroded channel floor (unit *Hchh*) (*Rotto and Tanaka*, 1995).

A geomorphologic map depicting some of the moats in their geologic context is shown in figure 12.3. A distinct, step-like topographic scarp with a height of more than 1000 m separates the terrace from the plateau of Tempe Terra in the north (ridged plains material; units *Hr* and *Hrd*).

Several mesas (*inselberge*; e.g., Labeatis Mensa) with heights of several 100 m to 1000 m are distributed on this terrace, mainly in its western part. These mesa

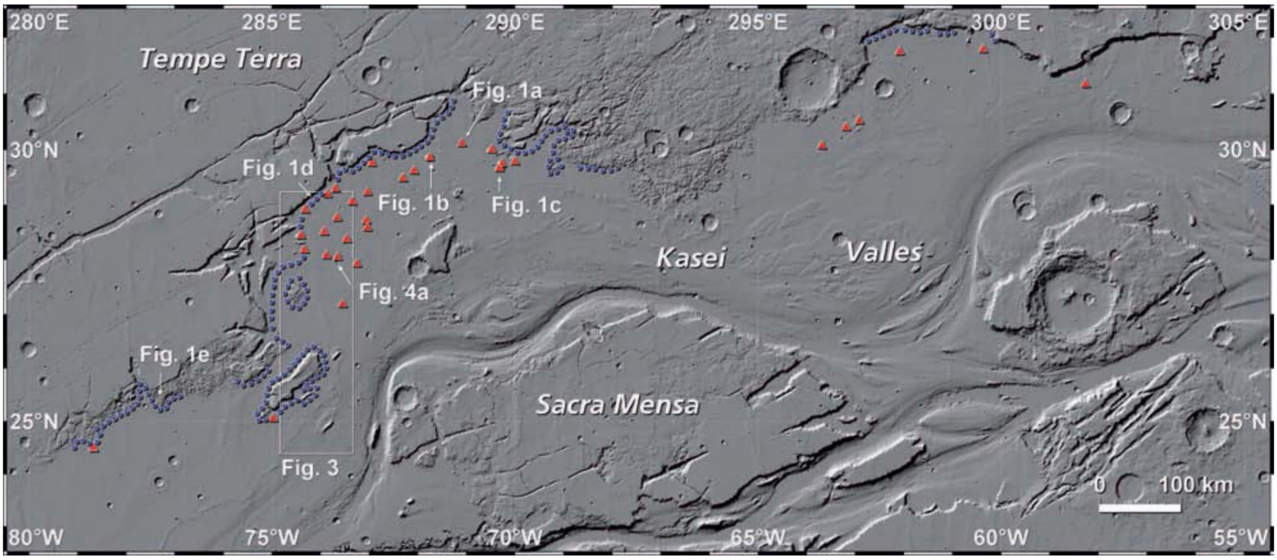

Figure 12.5.: Map of study area in northern Kasei Valles. Red symbols mark locations of free-standing mesas with enclosing depressions (e.g., figures 12.1a-c). Blue symbols mark topographic scarps with topographic depressions along their base (e.g., figure 12.1d-e). The occurrences east of about 293°E are less developed than those west of it. Base of map is a shaded version of griddded MOLA topographic data.

surfaces also consist of Hesperian ridged plains material. The terrace itself slopes very gently (~0.13°) towards the northeast (western part) and east (eastern part).

12.3. Morphology and Distribution

Morphology: Image data show a topographic scarp facing steep and high topographic walls of mesas or plateau margins (figure 12.4a). The outlines of these depressions have shapes and sizes in plan view that are identical to the outlines of intact lobate debris aprons (figure 12.4b) as confirmed by area measurements on isolated remnants and aprons which show a mean size ratio of 2.5 (ranging from 1.5 to 3.5), closely comparing to values obtained for intact remnants and debris aprons in Tempe Terra (*van Gasselt et al.*, 2003a). The topographic depression between the scarp and the mesa walls typically has a depth of more than 50 m (figures 12.4c-d). The floor of this depression is almost flat, and the topographic slope rising towards the mesa walls is less than 0.4°. In contrast, the surfaces of intact lobate debris aprons have slopes of around 1° to >12° (*Pierce and Crown*, 2003; *Carr*, 2001; *van Gasselt et al.*, 2003a) (figure 12.4e). At several locations, the scarps display a lobate morphology. At least at one moat around a mesa centered at 28.02°N and 286.32°E, a high-resolution MOC image (M12-01407) shows that the scarp has an elevated margin.

Distribution: Topographic depressions very similar to the examples shown in figure 12.1 exist around mesas and parallel to the southern plateau margins of Tempe Terra. They occur at latitudes between 25°N and 31°N, and between 281°E and 301°E (figure 12.5). These locations are distinctively south of the locations of modern and intact LDA previously mapped by *Squyres* (1979) and *Squyres and Carr* (1986) (figure 12.6). They are also south of the latitude belts at which *Kreslavsky and Head* (2000) and *Mustard et al.* (2001) found evidence for young mantling deposits indicative of a recent climate change. Both studies give a lower latitude limit of 30°N for these mantling deposits in the northern hemisphere, although *Mustard et al.* (2001) note that such deposits can be found at 25°S in the southern hemisphere.

In order to find out if this phenomenon is global, we searched for comparable moats at similar or even lower latitudes, where relatively young lava or sed-

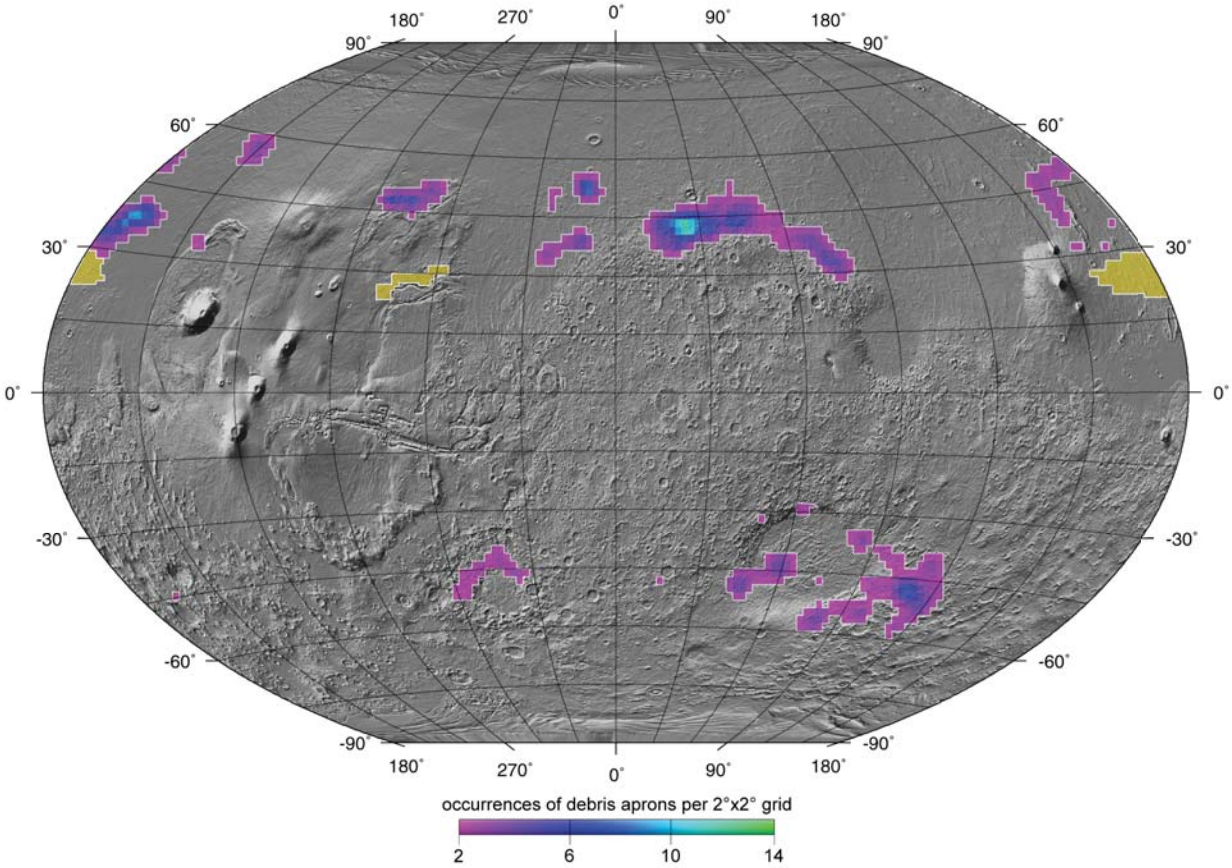

Figure 12.6.: Global distribution of modern and intact lobate debris aprons (colour-coded isodensities) and locations of former LDA in Kasei Valles and east of Elysium (yellow). Densities have been calculated based on debris-apron observations on Viking imagery and MOLA topography data. Note the latitude of <30° of the former LDA, indicating a paleoclimate with more precipitation at mid- and low latitudes than today. Basemap is global MOLA shaded relief map.

iment has embayed mesas and topographic scarps (e.g., in Elysium Planitia or at the southern parts of the Phlegra Montes). Several examples, though less developed than in Kasei Valles, were found around small knobs and mesas in the Tartarus Colles region, east of the Elysium volcanic rise (figure 12.7). They are embayed by Early Amazonian lava flows of the Elysium volcanic region (unit *AHEe* by *Tanaka et al.* (2005)) and by Late Amazonian lava flows in Marte Vallis (unit AEc_3 by *Tanaka et al.* (2005)).

The locations of these samples are between 24°N and 29°N latitude (figure 12.6). These moats are different from moats around knobs in the flood tract of Grjotá Valles, also in roughly the same region east of Elysium, but located more southwards (at latitudes of 14°S to 16°S). The moats there have different shapes in plan view, are smaller, and are ascribed to erosion by floodwaters (*Burr and Parker*, 2006).

Chronology: The basement of the study area consists of Hesperian-aged ridged plains (*Rotto and Tanaka*, 1995) (units *ps* and *epm in figure 12.3*. The events that incised Kasei Valles eroded these plains down to the grooved valley floor (unit *gvf* in figure 12.3). The material that flooded the valley floor in northern Kasei Valles and embayed the ancient lobate debris aprons (unit *fm* in figure 12.3) is stratigraphically higher than the valley floor and therefore younger. Its age was determined by *Lanz* (2003), p. 137, as 1.1 Ga on the basis of crater counts, using the production function of *Ivanov* (2001) and the cratering model of *Hartmann*

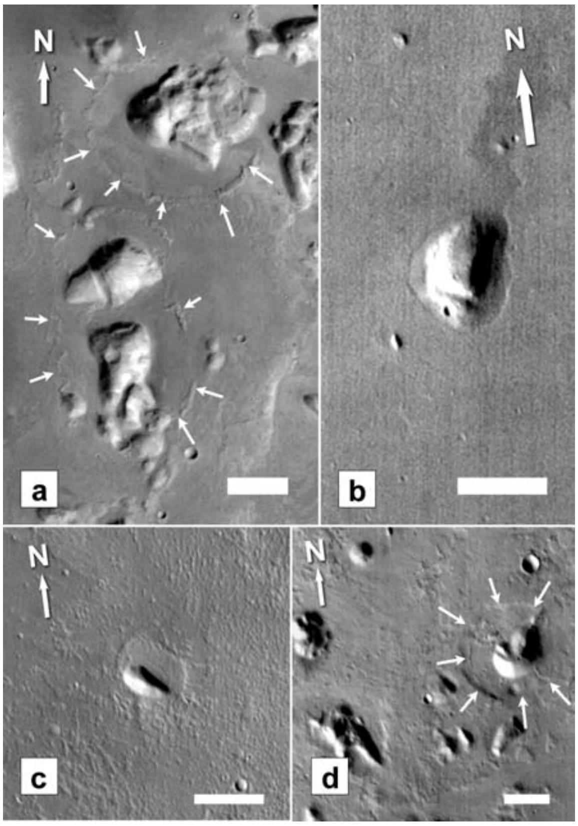

Figure 12.7: Examples of topographic depressions enclosing small knobs and mesas in the Tartarus Colles region and Marte Vallis east of Elysium. These moats are interpreted to represent the areas of former lobate debris aprons. (a) Circular accumulations of moraine-like material surround mesas. These landforms resemble those at the base of modern lobate debris aprons (compare with figure 12.4b; see also figure 12c of *Chuang and Crown* (2005b)). Detail of HRSC image 1562, centered at 25.52°N and 174.85°E. (b) Isolated mesa enclosed by depression. Detail of THEMIS-IR image I18291024, centered at 24.97°N and 188.75°E. (c) Isolated mesa enclosed by depression. Detail of THEMIS-IR image I01754007, centered at 27.66°N and 174.54°E. (d) Isolated mesas enclosed by depressions. Detail of THEMIS-IR image I17805021, centered at 24.53°N and 188.59°E. Scale bar for all images is 5 km.

and Neukum (2001) to derive absolute model ages.

We performed own crater counts (see figure 12.3 for location of counting area), using the same techniques, and obtain an absolute crater model age of 1 Ga to 1.6 Ga (figure 12.8). The lava emplacement in the Tartarus Colles region was determined to be of Early Amazonian age in the western parts and Late Amazonian age in the eastern parts (Marte Vallis) (*Tanaka et al.*, 2005).

12.4. Discussion

Based on the striking morphological similarity with modern LDA, we interpret the moats around the mesas and along the plateau scarps as an indication of the extents of former lobate debris aprons. Several scenarios could explain the current-day existence of moats at the sites of former debris aprons: Material flowing down from the Tharsis rise in the southwest could have flooded the floor of northern Kasei Valles no later than 1 Ga ago. This material could have consisted of lava flows (*Rotto and Tanaka*, 1995) and/or debris flows like lahars. Lahars have been proposed by several authors in the Elysium (e.g., *Christiansen*, 1989; *Russell and Head*, 2003) and Tharsis (e.g., *Tanaka*, 1989) regions, and they have also been suggested to account for deposits in several outflow channels, including Kasei Valles (*Tanaka*, 1999). The study area in northern Kasei Valles is located far away from volcanic source regions, but a runout distance of more than 1000 km has been reported from suggested megalahars on the northwestern slope of the Elysium volcanic rise (*Christiansen*, 1989). Where the flooding material terminated against lobate debris aprons and solidified, it formed a steep scarp.

This phenomenon is well known for lava flows on the Earth. Examples can be found in (a) the Garibaldi Volcanic Belt in British Columbia (Canada), where lavas from high-altitude vents flowed downhill to be impounded against ice (*Matthews*, 1952), (b) at the Llangorse volcanic field in northern British Columbia (Canada) (*Harder and Russell*, 2007), or (c) at Mount Rainier (Washington, USA), where lava flows were emplaced between valley glaciers and remain as to-

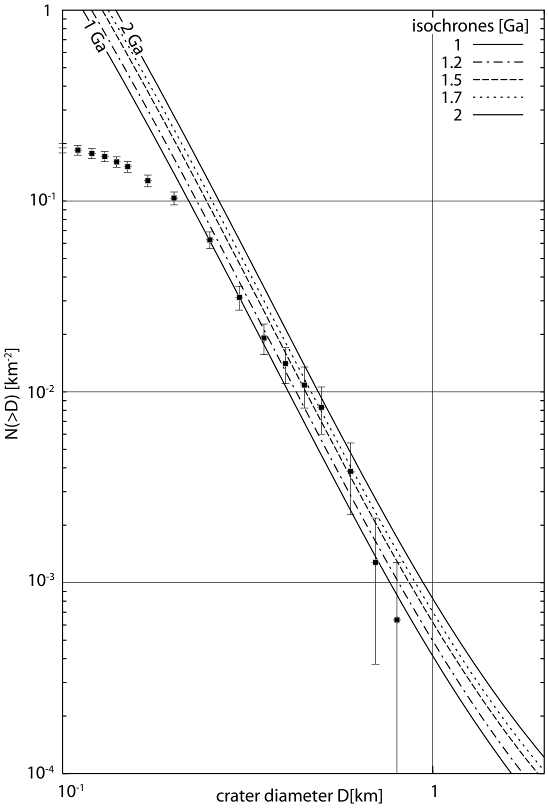

Figure 12.8: Crater-size frequency plot and isochrones of measurement area (1565.6 km^2; see figure 12.3c for location), isochrones based upon chronology model function coefficients by *Ivanov* (2001) and production function coefficients by *Hartmann and Neukum* (2001) (N=322, D=0.05-0.89 km). Multiple phases of resurfacing processes (e.g., lava flows of different ages, or subsequent emplacement of debris flows) cause kinks in the distribution, average age is determined between 1.1 Ga and 1.7 Ga, for a discussion on errors see *Neukum et al.* (2004).

pographic ridges after the glaciers retreated (*Lescinsky and Sisson*, 1998). The phenomenon has also been observed for the case of Mars: In a similar way, lava flows seem to have banked against the glacier that might have been present at Pavonis Mons (see figure 23 in (*Shean et al.*, 2005a)). Indeed, typical lobate terminations of possible lava flows can be observed in new image data (figure 12.9a). An origin of the flooding material as lahars might be supported by the observation of several channels in the immediate vicinity of the moats (figure 12.9b), which might have been formed by de-watering of water-rich lahar deposits.

However, it can not be excluded that the channels were carved by the latest and very minor stages of Kasei Valles outflow activity. Finally, erosion beneath the former lobate debris aprons might also have contributed to the formation of the moats, and the elevated margins of the scarps at several locations (e.g., figure 12.1e) might be interpreted as push moraines. Based on the strong evidence for lobate lava flow terminations (figure 12.9a) we favour lava flows as the most likely material to preserve the moats, although we can not rule out other hypotheses.

We conclude that the combination of relatively young lava (and/or debris flows) and the occurrence of topographic relief is particularly suitable to create these depressions. Lobate debris aprons might have formed in the past at other places in low latitudes as well, but were not preserved by embaying lava flows or other deposits like mud flows.

After LDA were removed by thermokarstic degradation through the sublimation of ice and deflation of detritus (*Mangold*, 2003; *Crown et al.*, 2003; *Pierce and Crown*, 2003) (see also figure 1 in *Head et al.* (2005), which shows fretted pits and depressions that suggest the former presence of ice), the solidified lava front remains as a free-standing topographic cliff (figure 12.10). The same moats were first mentioned by *Lucchitta and Chapman* (1988) and later described by *Chapman and Scott* (1989) and *Chapman et al.* (1991), who used photoclinometric profiles to measure a depth of the moats of about 40 m and noted that

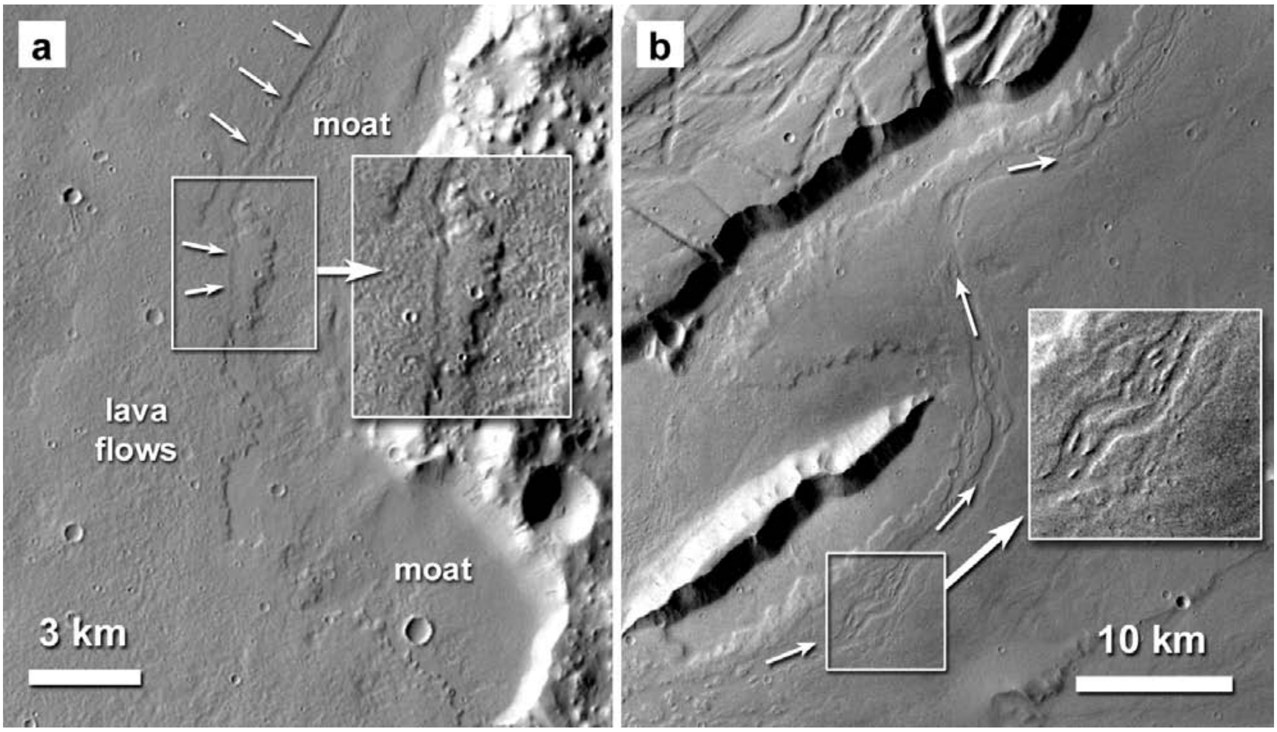

Figure 12.9.: Details of the contact between moats and mesa-embaying material. (a) Abrupt termination of older lava flows (white arrows) forming a moat around a mesa, and younger lobate lava flows (enlarged in inset) that overtopped the older flows and partly filles the moat (detail of THEMIS-VIS image V11948006; location is marked in figure 12.3); (b) Anastomosing channels with streamlined "‘islands"’, probably carved by water in the vicinity of moat around mesa (arrows). The water could have been released by the de-watering of lahar deposits, or it might have been associated with minor and very late stage outflow activity in Kasei Valles (detail of HRSC image 3217; location is marked in figure 12.5).

the moats have flat floors. They ascribed the moats to lava flows that "terminated upwards against former slopes at the base of talus material", and suggest that the talus might have consisted of fine detritus and ice, which was subsequently deflated and melted, respectively. This interpretation does not explicitly mention LDA, but is in line with our hypothesis. If this schematic model is correct, it would also imply that modern LDA are indeed ice-rich deposits analogous to rock glaciers (*Barsch*, 1996).

Since the use of the term rock glacier on Mars is problematic, because of the difficulty that rock glaciers on Earth can form in several ways (*Whalley and Azizi*, 2003), we note here that using this term we do not intend to favour a specific origin. Rather, we use it as a non-generic term to refer to a tongue-like or lobate body resembling a small glacier, a definition that is derived from, but more general than the definitions given by, e.g., (*Washburn*, 1979a) or (*Barsch*, 1996), and would for this purpose also include debris-covered glaciers (e.g., *Head et al.*, 2006b).

The almost flat floor of the moats suggests that the entire amount of the material originally constituting the LDA has been removed. This fact has one or more of the following implications: Either the LDA had a very high percentage of ice that sublimated away, Kasei floodwaters eroded the friable materials, or the clastic fraction of the LDA consisted mainly of very fine material, i.e. dust-sized particles (comparable to loess), which could be easily removed by wind. If coarse clastic particles (coarser than sand-sized) had made up a significant fraction of the former LDA, relicts of that material should still be seen on the floor since the fine material is more effectively removed by wind (e.g., *Armstrong and Leovy*, 2005). *Mangold and Allemand* (2001) have pointed out that the volumes of some LDA are too large to have been derived from rockfalls from the associated mesas. A high ice content and/or a significant content of atmospheric dust in the total volumes of these LDA would not only explain their relatively large volume with respect to the associated mesa. The small particle sizes implied by atmospheric dust would also explain the almost complete loss of material and the remaining flat floors, since these small-sized particles would be more easily eroded by wind than coarser-grained materials.

A very high ice content is consistent with the modelling results of *Colaprete and Jakosky* (1998) and *Li et al.* (2005), which show that a high content of solid particles in rock glaciers prevents flow. Since the former lobate debris aprons seem to have flowed from the mesa radially outwards, a high ice content might have facilitated this flow. If modern LDA have a comparable morphology to the ancient LDA in northern Kasei Valles, the contact between the LDA and the underlying bedrock should also be flat. This could be tested with the Shallow Subsurface Radar (SHARAD) on the Mars Reconnaissance Orbiter (MRO) (*Seu et al.*, 2004), which has a horizontal resolution between 0.3 km and 3 km and a vertical resolution of 15 m in free space (better than 10 m in Mars' subsurface), sufficient to resolve the dimensions of LDA.

Virtually all modern and intact lobate debris aprons are located polewards of ±30°. This distribution is thought to reflect the influence of climatic conditions on the formation of features indicative of creep of ice and debris. The climate on Mars is controlled by the obliquity of the planet's rotational axis and by the orbital parameters eccentricity and precession (e.g., *Murray et al.*, 1973; *Pollack*, 1979; *Toon et al.*, 1980; *Jakosky et al.*, 1995; *Laskar et al.*, 2004). At higher obliquities than today (~25°), ground ice becomes stable even in equatorial latitudes (e.g., *Mellon and Jakosky*, 1995). It was also shown by climate modelling that prolonged periods of higher obliquity lead to a mobilization of volatiles at the poles and to precipitation at low latitudes (*Levrard et al.*, 2004; *Forget et al.*, 2006). The obliquity of Mars is variable, but can not be reliably predicted backwards in time for more than about 10^7 years due to its chaotic behavior (*Touma and Wisdom*, 1993; *Laskar and Robutel*, 1993). However, recent calculations suggest that the averaged obliquity over 5 Ga was probably almost 40° (*Laskar et al.*, 2004), a value that would allow ground ice to be stable globally. Our results indicate the formation of lobate debris aprons and the stability of ground ice equatorwards of ±30° more than 1 Ga ago and are therefore consistent with such models of the evolution of Mars' obliquity that predict an averaged higher obliquity (*Laskar et al.*, 2004). Higher obliquities in the past could have lead to precipitation of snow at low latitudes, where lobate debris aprons formed because ground ice would have been stable. After the embayment of lobate debris aprons by lava flows, the disappearance of the lobate debris aprons would have been triggered by a decrease in the obliquity and the associated instability of ground ice at low latitudes. Periodic variations of the obliquity in the past might have caused the formation and entire removal by wind of lobate debris aprons many times in the past, as suggested earlier by *Lucchitta* (1984). New image data suggest that climate change may have occurred (and lobate debris aprons were removed) during emplacement of lava flows or sedimentary materials like lahars (unit *At4* as mapped by *Rotto and Tanaka* (1995)), as some younger lava flows can be observed that flow into the topographic depressions of the moats (figure 12.9a).

12.5. Conclusions

[1] Topographic depressions around mesas and along the base of plateau scarps in the northern Kasei Valles region are interpreted as areas previously occupied by lobate debris aprons, which are generally considered to consist of mixtures of ice and debris, analogous to terrestrial rock glaciers. Lava flows and/or debris flows (lahars) embayed former lobate debris aprons, and after removal of the lobate debris aprons material through the complete loss of volatiles and deflation of the debris constituents, the solidified lava front preserved the "fingerprints" of ancient lobate debris aprons.

[2] Very similar landforms in the Tartarus Colles re-

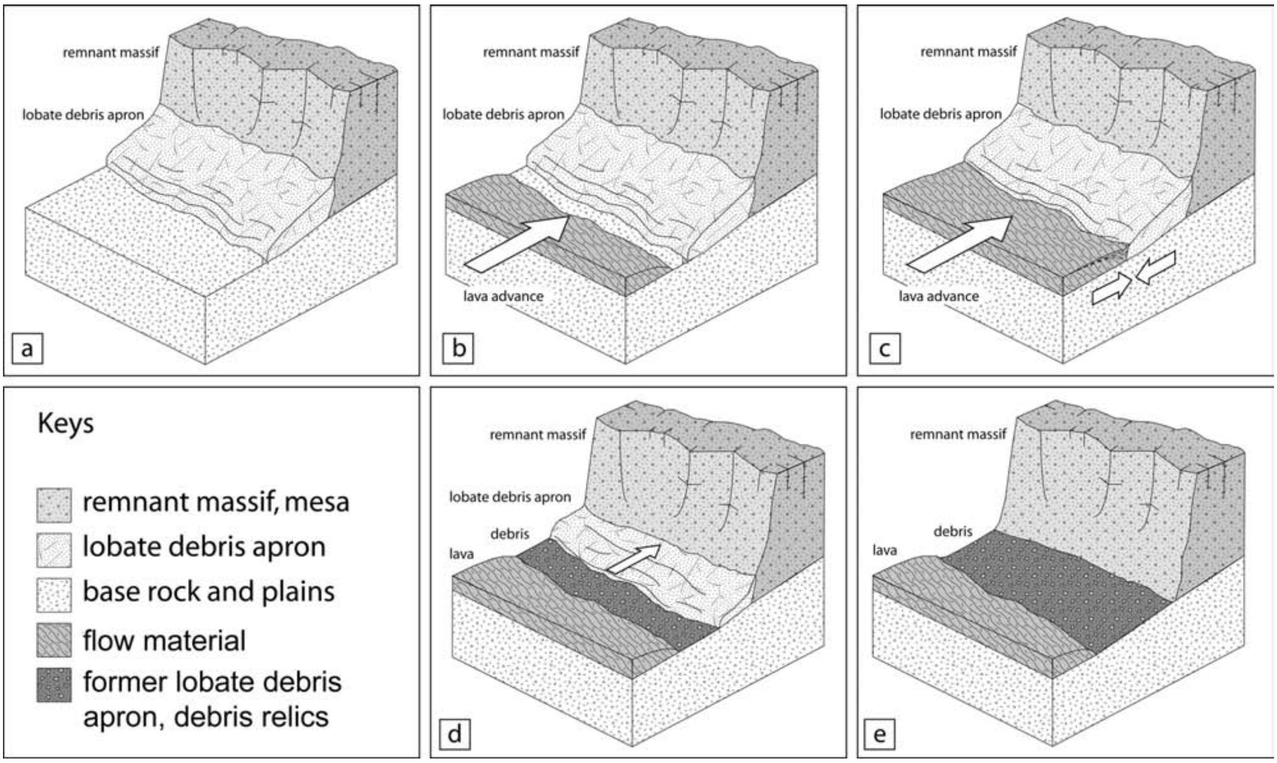

Figure 12.10.: Schematic model of landscape genesis. (a) Lobate debris apron (LDA) exists around a mesa or along a linear topographic scarp. (b) Lava or debris flow front advances towards the LDA. (c) Lava flow or debris flow (e.g., lahar) terminates against LDA flow front and solidifies. (d) LDA retreat due to climate change and beginning formation of depression. (e) Remaining depression after complete removal of LDA material, present situation.

gion between 24°N and 29°N are also interpreted as the relicts of former lobate debris aprons. They are embayed by early Amazonian lava flows from the Elysium rise and by late Amazonian lava flows covering the Marte Vallis area.

[3] The flat floors of these moats indicate that nearly the entire material of the former lobate debris aprons has been removed. This implies a very high ice content of the former lobate debris aprons, or a predominance of relatively small-sized particles in the debris of the lobate debris aprons, which could easily be removed by deflation, or both. This part of our hypothesis can be tested by data that will be obtained with the radar experiment SHARAD onboard NASA‘s Mars Reconnaissance Orbiter mission: If modern lobate debris aprons are similar to the ancient lobate debris aprons that were analyzed in this study, the high ice content of the lobate debris aprons should only weakly attenuate the radar signals and allow them to penetrate down to the underlying substrate. Therefore, the bottom of the lobate debris aprons should be visible, analogous to the underlying substrate beneath the south polar caps in MARSIS data (*Plaut et al.*, 2007).

[4] The former lobate debris aprons existed around 1 Ga ago at latitudes between 25°N and 30°N, which is equatorwards of the latitudinal belts where modern lobate debris aprons are observed today. The occurrence of ancient rock glaciers at these latitudes can be explained by a higher than present paleo-obliquity, which is consistent with recent modelling of the obliquity evolution indicating an averaged obliquity of nearly 40° over 5 Ga (*Laskar et al.*, 2004), in accordance to assumptions by *Lucchitta* (1984); *Head et al.* (2005).

[5] Our observations suggest that the surface of Mars might have been repeatedly affected by the effects of climate changes leading to lobate debris aprons for-

mation and destruction in the past (*Lucchitta*, 1984), and that glacial and periglacial processes might have had a significant impact in landscape genesis even at latitudes lower than $\lesssim 30^\circ$ over a large fraction of Mars' geologic history.

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Note:

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