Concentric crater fill in Utopia Planitia: History and interaction between glacial “brain terrain” and periglacial mantle processes

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ABSTRACT

At martian mid-to-high latitudes, the surfaces of potentially ice-rich features, including concentric crater fill, lobate debris aprons, and lined valley fill, typically display a complex texture known as “brain terrain,” due to its resemblance to the complex patterns on brain surfaces. In order to determine the structure and developmental history of concentric crater fill and overlying latitude-dependent mantle (LDM) material, “brain terrain” and polygonally-patterned LDM surfaces are analyzed using HiRISE images from four craters in Utopia Planitia containing concentric crater fill. “Brain terrain” and mantle surface textures are classified based on morphological characteristics: (1) closed-cell “brain terrain,” (2) open-cell “brain terrain,” (3) high-center mantle polygons, and (4) low-center mantle polygons. A combined glacial and thermal-contraction cracking model is proposed for the formation and modification of the “brain terrain” texture of concentric crater fill. A similar model, related to thermal contraction cracking and differential sublimation of underlying ice, is proposed for the formation and development of polygonally patterned mantle material. Both models require atmospheric deposition of ice, likely during periods of high obliquity, but do not require wet active layer processes. Crater dating of “brain terrain” and mantled surfaces suggests a transition at martian mid-latitudes from peak “glacial” conditions occurring within the past ∼10–100 My to a quiescent period followed by a cold-desert “periglacial” period during the past ∼1–2 My.

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1. Introduction

Glaciation, and ice-related processes, have shaped martian mid- and high latitudes during the late Amazonian (Mustard et al., 2001; Kreslavsky and Head, 2002; Head et al., 2003, 2006a; Kuzmin, 2005; Forget et al., 2006; Fastook et al., 2008; Head and Marchant, 2009). The record of variable Amazonian climate conditions is indicated by a variety of martian landforms (Marchant and Head, 2007), including the latitude-dependent mantle (LDM) (Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003; Schon et al., 2008); concentric crater fill, lobate debris aprons, and lined valley fill (Squyres, 1979; Lucchitta, 1984; Squyres and Carr, 1986; Head et al., 2006b); polygonally patterned ground (Mangold, 2005; Levy et al., 2009; Mellon et al., 2008); and pedestal craters (Kadish and Barlow, 2006; Kadish et al., 2008). Questions arise as to the nature and timing of Amazonian climate change, and whether conditions that might have led to melting have occurred (Kreslavsky et al., 2008; Soare et al., 2008). Further, unusual textures are observed on the surfaces of many Amazonian examples of concentric crater fill, lined valley fill, and lobate debris aprons. These textures include pit-and-butte texture (Mangold, 2003), “knobs—brain coral” (Williams et al., 2008), “brain coral terrain” (Dobrea et al., 2007), or, succinctly, “brain terrain” (Levy et al., 2009); the origin, age, and climate conditions represented by these surface textures remain an area of active research.

We examine concentric crater fill surface textures in Utopia Planitia in order to assess initial emplacement conditions and processes (Figs. 1 and 2). We document relationships between concentric crater fill surfaces and overlying latitude-dependent mantle (LDM) material (hereafter referred to simply as mantle material) in four Utopia Planitia craters. Finally, we date these surfaces using crater retention ages and propose a model for their formation, and modification history. Although several hypotheses have been suggested for the origin of concentric crater fill, ranging from aeolian modification (Zimbelman et al., 1989) to rock-glacier processes (Mangold and Allemand, 2001), linedate and lobate concentric crater fill surface patterns strongly indicate glacier-like flow (Head et al., 2006a; Levy et al., 2007). “Brain terrain” appears to be a modification of concentric crater fill lobe and lineation patterns. In contrast, the latitude-dependent mantle (LDM) is described as a flat-lying, or draped surface unit, meters to tens of meters thick, which has a variety of characteristic surface textures, including
Fig. 1. Context map of study area in Utopia Planitia. Individual HiRISE image locations are shown. Base map is MOLA shaded relief topography.

Fig. 2. Image location maps for subsequent figures. (a) Concentric crater fill and mantle material from PSP_002782_2230 over CTX image P03_002782_2232. North to image top and illumination is from the lower left. (b) Concentric crater fill and mantle material from PSP_002175_2210 over CTX image P01_002175_2211. North to image top and illumination is from the lower left.
polygonal patterning, pitting, and scalloping (Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003; Schon et al., 2008). In the Utopia Planitia study region, both “brain terrain” and polygonally patterned mantle are present and in some locations, “brain terrain” underlies the polygonally patterned mantle. Detailed analysis of polygon morphology at the mantle surface provides insight into the processes of mantle emplacement, and in places, of interactions and modification of the underlying “brain terrain.” These morphological and stratigraphic relationships permit us to reconstruct a history of ice-related processes in the martian middle-to-high latitudes during the recent Amazonian. These processes range from debris-covered glacial activity (i.e., the formation of alpine and debris-covered glaciers that remain long-lived due to the preservative effects of capping sublimation lags) (Marchant et al., 2002; Kowaléwski et al., 2006) to cold desert “periglacial” processes (cold-climate, non-glacial geomorphological processes such as permafrost development, thermal contraction cracking, etc.) (Washburn, 1973).

2. Morphology

2.1. “Brain terrain”

At HiRISE resolution (~30 cm/pixel), the surface of concentric-crater-fill “brain terrain” displays a complex morphology composed of smaller, discrete surface structures that we term “cells.” Two distinct textures are commonly present in “brain terrain” observed in Utopia Planitia concentric crater fill: closed-cell “brain terrain” and open-cell “brain terrain” (Figs. 3–5). Similar features have been observed elsewhere, notably on lineated valley fill and lobate debris apron surfaces (Williams et al., 2008; Dobrea et al., 2007).

Closed-cell “brain terrain” in Utopia Planitia exhibits arcuate, mounded cells with both flat and rounded upper surfaces. Cells are commonly ~10–20 m wide, ~10–100 m long, and ~4–5 m high (based on HiRISE image shadow measurements). Some closed-cell “brain terrain” cells have surface grooves or furrows located near the centerline of the long axis (Figs. 6–8). Closed-cell “brain terrain” cells occur singly, or in linked groups (Figs. 6–8). Closed-cell “brain terrain” cells commonly form lineations that are oriented concentrically to the crater in which the unit is present (Figs. 5, 9 and 10). Spacing between closed-cell “brain terrain” lineations is variable, but is commonly ~20 m (Figs. 5–8). Closed-cell “brain terrain” is commonly present on undulating topography, at the top of concentric ridges (and sometimes in the concentric valleys between ridges) (Figs. 5, 9 and 10).

Some closed-cell “brain terrain” units have a strongly polygonal surface texture (compare closed-cell “brain terrain” mounds in Fig. 6 to Figs. 7 and 8). Open-cell “brain terrain” commonly features a surface furrow oriented axially at the center of the mound-shaped cell (Figs. 7 and 8).

Open-cell “brain terrain” is composed of arcuate and cuspatate cells that are delimited by a convex-up boundary ridge, commonly ~4–6 m wide and ~2 m high (based on HiRISE image shadow measurements), surrounding a flat-floored depression (Figs. 3–5). Open-cell “brain terrain” cells are of similar dimensions to closed-cell “brain terrain” cells. Open-cell “brain terrain” boundary ridges

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**Fig. 3.** (a) Closed-cell “brain terrain.” Sinuous, elevated “cells” are approximately 20 m wide, and up to ~100 m long. Image is 200 m wide. North to image top. Portion of PSP_002175_2210. (b) Open-cell “brain terrain.” Sinuous ridges of positive topography outline flat-floored “cells.” Images is 200 m wide. North to upper right. Portion of PSP_002175_2210. (c) High-center mantle polygons. Image is 200 m wide. North to image top. Portion of PSP_002175_2210. (d) Low-center mantle polygons. Image is 100 m wide. North to image top. Portion of PSP_002782_2230.
are commonly parallel along the long axis, but may be tightly rounded or gradually tapered along the short axis (Figs. 3–5). Open-cell “brain terrain” cells occur singly, or in linked groups (Figs. 3–5). Open-cell “brain terrain” cells commonly form lineations that are oriented concentrically to the crater in which the unit is present (Figs. 5, 9 and 10). Open-cell “brain terrain” lineation spacing is variable, but is commonly ~20 m. Open-cell “brain terrain” is commonly present at the lateral contact between “brain terrain” and the mantle (Figs. 3–5), and in topographically low valleys between “brain terrain” ridges (Figs. 9 and 10). Open-cell “brain terrain” is also common in topographic lows between closed-cell “brain terrain”-patterned ridges and hills (Figs. 3–5 and 10).

Boulders are present on the surface of both open-cell and closed-cell “brain terrain,” and are typically less than 2 m in diameter (Figs. 3 and 5). Boulders are most commonly found atop closed-cell mounds and on open-cell boundary bands, although some boulders are present in topographic lows.

2.2. Polygonalized mantle

In the analyzed craters, mantle material is present in a continuous ring around the crater interior wall, and as patchy occurrences in topographic lows between crater fill ridges. Mantle material present in proximity to “brain terrain” is polygonally patterned and displays two distinct textures (Fig. 3): high-center mantle polygons and low-center mantle polygons (Figs. 11 and 12). High-center mantle polygons are bounded by depressed surface troughs which intersect at both near-orthogonal and near-hexagonal intersections, forming polygonal patterns with topographically high interiors rel-
Fig. 6. Closed-cell "brain terrain" present in PSP_002175_2210. Axial furrows are present along some "brain terrain" mounds (arrows). North to image top. Illumination is from the left.

Fig. 7. Contact between strongly lineated closed-cell "brain terrain" (left) and polygonal closed-cell "brain terrain" (right). Axial furrows are present in many closed-cell "brain terrain" mounds (Arrows). Portion of PSP_002782_2230. Illumination is from the lower left. North to image top.

ative to their boundaries (Figs. 11 and 12). High-center mantle polygons are commonly \( \sim 10 \) m in diameter, with slightly convex-up interiors. High-center mantle polygon troughs are commonly \( \sim 2-3 \) m across. The mantle material in which high-center polygons are present can be up to \( \sim 40 \) m thick, based on MOLA point measurements, but thins and pinches out at lateral contacts with "brain terrain" and steep crater wall surfaces. On average, mantle material in the examined craters must be thick enough to smooth-over topographic undulations in underlying "brain terrain"—likely indicating a typical depth of 10–20 m. The mantle unit is generally flat, and is bounded by gently sloping margins, as well as by steeply scarped, scalloped margins (Figs. 11 and 12).

Low-center mantle polygons (Figs. 3, 11 and 12) are composed of troughs with raised shoulders that intersect near-orthogonal and near-hexagonal intersections, forming polygons with depressed centers, relative to their raised rims (Figs. 11 and 12). Low-center mantle polygons are commonly \( \sim 10 \) m in diameter (but may be as small as \( \sim 5 \) m in diameter, e.g., Fig. 12), and have smooth, flat, depressed interiors. Low-center mantle polygon troughs are commonly \( \sim 3-4 \) m wide. Low-center mantle polygons are found at the fringes of the mantle, at both gradual and scalloped margins (Figs. 11 and 12).

2.3. Spatial relationships between brain terrain and mantle polygons

Whereas the superposition relationship between mantle material and "brain terrain" is generally clear, detailed mapping reveals locally complex lateral contacts between "brain terrain" and mantle material (Fig. 13). At lateral contacts between mantle and "brain terrain" units, mantle material is commonly draped on, and inter-fingered between, "brain terrain" "cells," suggesting that mantle material superposes, and in places, embays "brain terrain" units.
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Fig. 8. Closed-cell “brain terrain” with pronounced axial furrows (arrows) at the confluence of two concentric crater fill lobes in PSP_002782_2230. North to image top. Illumination is from the left.

Fig. 9. Three-dimensional surface structure of concentric crater fill and mantle material. “Brain terrain” visible at full resolution appears as knobby surface roughness and is strongly lineated concentric to the crater, with concentric ridges and valleys observable. “Brain terrain”-covering LDM material is located around the crater interior wall, and in low areas between “brain terrain”-patterned ridges. Crater is ~10 km in diameter. North to image top. Red–blue (left/right) anaglyph is a portion of stereo pair PSP_002175_2210 and PSP_001410_2210. Anaglyph produced by James Dickson.

Fig. 10. Close-up view of concentric crater fill ridges and valleys present in Fig. 9 (right side, below middle). Ridges are surfaced with closed-cell and some open-cell “brain terrain.” Valleys are surfaced primarily by open-cell “brain terrain.” Red–blue (left/right) anaglyph is a portion of stereo pair PSP_002175_2210 and PSP_001410_2210, and is ~2 km wide. North to image top. Anaglyph produced by James Dickson.

(Figs. 4, 14, and 15). Mantle material is commonly found at the foot of crater interior wall slopes, and in topographic lows between “brain terrain”-surface concentric ridges within craters (Figs. 9 and 10). Exposures of underlying “brain terrain” microtopography crop out through the mantle, suggesting that the mantle thins and pinches out at lateral contacts with “brain terrain” (Figs. 14 and 15). Topographically high exposures of closed-cell “brain terrain” are commonly ringed by open-cell “brain terrain,” which is in turn ringed by mantled surfaces patterned with low-center, and/or high-center mantle polygons (Figs. 4 and 5). Concentric crater fill ridges surfaced by closed-cell “brain terrain” are commonly flanked by open-cell “brain terrain” in the lows between ridges, particularly in lows that also have exposures of mantle material (Figs. 10,
Fig. 11. Low-center mantle polygons (LC-MP) present in a scalloped depression in PSP_002782_2230. High-center mantle polygons (HC-MP) surround the low-center mantle polygons, both within, and outside the depression. Illumination is from the lower left. North to image top.

Fig. 12. Low-center mantle polygons (LC-MP) present along a gently sloping contact between high-center mantle polygons (HC-MP) and “brain terrain” (CC-BT) in PSP_002782_2230. Illumination is from the lower left. North to image top.

Open-cell “brain terrain” is rarely observed without near-by and/or overlying mantle material, and low-center mantle polygons are not observed in isolation from extensive regions patterned by high-center mantle polygons.

Complete transitions between surfaces dominated by high-center mantle polygons, low-center mantle polygons, open-cell “brain terrain,” and closed-cell “brain terrain” occur on length scales of ~100–500 m in the analyzed images (Fig. 15). Lateral contacts between mantle surfaces patterned with high-center and low-center mantle polygons are gradational on gentle slopes and abrupt on steeply scalloped slopes (Figs. 11 and 12). Lateral contacts between closed-cell “brain terrain” and open-cell “brain terrain” are gradational, consisting of closed-cell “brain terrain” cells that are partially depressed, or that transition into open-cell “brain terrain”–like boundary ridges (Figs. 4 and 5). A schematic stratigraphy of “brain terrain” and polygonally patterned mantle surface textures is shown in Fig. 16.

3. Surface ages

Crater counting on concentric crater fill and mantle terrains is complicated by the obscuration and disruption of craters by brain terrain and mantle polygons (Mangold, 2003; Kostama et al., 2006). In this study, 168 craters were counted on mantle and “brain terrain” surfaces present in four HiRISE images. Only fresh craters showing no evidence of subsequent polygon formation within the crater were counted on mantle surfaces (e.g., Fig. 17a). Given that thermal contraction crack polygons can form during permafrost formation (syngenetic wedges) or after substrate degradation begins (epigenetic and anti-syngenetic wedges) (Mackay,
1990), counting only fresh, unfractured craters gives us a minimum age for the cessation of mantle emplacement. Counts on mantle surfaces indicate a minimum age of ~1.5 My (best-fit ages span 1.3 to 1.7 My using the Neukum (Neukum and Ivanov, 2001) and Hartmann (2005) production functions, respectively) (Fig. 18)—a youthful age consistent with earlier estimates of mantle ages elsewhere in the northern hemisphere (Head et al., 2003). For mantle surfaces displaying small thermal contraction crack polygons, a reduction in the abundance of ~20 m diameter craters on mantle surfaces is typical, and may result from the removal or obscuration of craters with diameters comparable to polygon diameters (Levy et al., 2009).

Crater counts on “brain terrain” are likewise complicated, owing to the obscuration of small craters by “brain terrain” cells, the destruction of small and medium-sized craters by “brain terrain” cell development, and the presence of craters with unusually modified morphologies (e.g., Mangold, 2003) (Fig. 17). Combined counts of fresh and modified craters (including “ring-mold” and/or “oyster
shell” craters (e.g., Mangold, 2003; Kress and Head, 2008) (Fig. 18), which “brain terrain” has developed) have been interpreted to be deformation of ice-rich materials. Boulder-sized clasts present on the concentric crater fill surface could represent rock-fall entrained at crater wall ice-accumulation zones, and transported to their present location by glacial flow (e.g., Marchant et al., 2002; Head and Marchant, 2006; Marchant and Head, 2007).

Gravitational stresses that drive brittle deformation of near-surface glacier ice, coupled with thermal stresses generated by seasonal heating and cooling (Mellon, 1997) would fracture the ice-rich crater fill, resulting in the generation of oriented fracture networks, analogous to those observed on flowing debris-covered glaciers on Earth (Fig. 20b) (Levy et al., 2006). This combination of stresses—thermal and glacial—can account for the variety of surface patterns and textures observed in “brain terrain.” Internal deformation of flowing ice-rich material generates the broad, first-order concentric lineation patterns observed in “brain terrain.” Lateral flow orients the near-surface stress field (Benn et al., 2003), aligning thermal contraction cracks both normal and orthogonal to the flow direction; alternatively, cracks may initially form in random patterns, but are oriented during subsequent flow of subsurface ice and debris (Marchant et al., 2002; Levy et al., 2006). These oriented fractures will develop into strongly oriented cracks and mounded-shaped closed-cell “brain terrain” (see below). Thermal contraction crack fractures will be less strongly oriented on “brain terrain” that has experienced minimal flow, resulting in only moderately oriented, and largely hexagonal fractures (Levy et al., 2006). In addition to the above, concentric crater fill might be thickest near the center of crater floors where transported debris overlying glacier ice is typically at a maximum (e.g., Head et al., 2008; Kowalewski, 2008) and where the temperature conditions are most favorable for ice preservation (Russell et al., 2004). These factors could result in a rise in the elevation of the crater fill at the center.
Fig. 15. Contacts between “brain terrain” and mantle polygon textures. A complete transition between high-center mantle polygons (HC-MP), low-center mantle polygons (LC-MP), open-cell “brain terrain” (OC-BT) and closed-cell “brain terrain” (CC-BT) is present in each panel. All panels are excerpted from PSP_002782_2230, with illumination from the left and north to image top in all panels.

Fig. 16. Schematic stratigraphy of “brain terrain” and mantle textures. The upper line is MOLA point topography. Lower lines delimit estimated subsurface boundaries between “brain terrain” and mantle. Brackets illustrate surface exposures of closed-cell “brain terrain” (CC-BT), open-cell “brain terrain” (OC-BT), high-center mantle polygons and low-center mantle polygons. MOLA is derived from a segment of orbit 12303 passing over HiRSE image PSP_002782_2230.

of craters relative to surrounding, lower-elevation, ablated surfaces of crater fill.

If an ice-free sublimation lag deposit is present on concentric crater fill surfaces (generated by a combination of aeolian sediment deposition, sublimation of underlying debris-rich ice, and desert pavement formation), interactions between thermal-contraction surface fractures and overlying lag deposits could result in the observed complex morphology of “brain terrain”
Fractures would initially represent sites of depressed surface troughs (Fig. 20c) (Marchant et al., 2002). This is because enhanced contact with the dry atmosphere at polygon fractures would result in greater sublimation of subsurface ice along polygon cracks (Marchant et al., 2002; Kowalewski et al., 2006, 2007), generating widened, deepened troughs analogous to those outlining terrestrial sublimation polygons (Marchant et al., 2002). Thermal fractures would accumulate sediment derived from winnowing of overlying lag deposits (e.g., Marchant et al., 2002) and infiltration of aeolian sediments, forming wedges analogous to sand-wedge structures common in cold and arid terrestrial environments (Fig. 20d) (Péwé, 1959; Berg and Black, 1966; Marchant et al., 2002; Marchant and Head, 2007). Lateral transport of surface materials into deepening troughs would result in ever-thicker accumulations of sediment relative to “stable” polygon interiors (e.g., Marchant et al., 2002).

Inversion of sublimation-polygon-like topography (polygons with convex-up centers) could occur if sublimation continued to remove near-surface ice at polygon centers, but slowed at polygon troughs due to the presence of thickened accumulations of sediment along polygon troughs (Fig. 20e) (e.g., Marchant et al., 2002). Cementation of wedge sediments at polygon margins by ice deposited during periods of reversed vapor flux would enhance the protection of ice located beneath the sediment wedges.
process could account for the formation of closed-cell “brain terrain” contemporaneously with and continuing after, the period of concentric crater fill flow.

The development of open-cell “brain terrain” could be accounted for in this topographic inversion model by the continued removal of ice from beneath closed-cell “brain terrain” cells. Continued removal of subsurface ice over time may explain the presence of open-cell “brain terrain” in topographic lows between closed-cell-patterned concentric ridges (e.g., Fig. 5). Additionally, where thin, dessicated remnants of low-albedo mantle material are draped over “brain terrain” cells at the pinched-out margins of the mantle (Fig. 15) we hypothesize that enhanced sublimation of residual ice beneath “brain terrain” cells (Williams et al., 2008) could further promote the collapse of closed-cell “brain terrain” cells, generating open-cell “brain terrain” cells (Fig. 20g).

This process for the formation and modification of “brain terrain” textures differs from that outlined by Mangold (2003) in that it invokes both glacial stress orientation, as well as thermal contraction cracking and sand-wedge development, to account for the detailed microrelief of “brain terrain” textures. It differs from the Dobrea et al. (2007) model in that the preservation of broad-scale glacial flow features and of thermal contraction crack polygon wedges are preserved in the “brain terrain”—which would be lost if cryoturbation or thermokarst formation (melting) had resulted in widespread reworking of the concentric crater fill surface. Our proposed process is illustrated schematically in Fig. 20. Lastly, some fractures, particularly those located near the margins of the crater, may have formed more recently than the observed “brain terrain” textures. Such fractures (e.g., Fig. 13) are interpreted to represent late-stage mechanical failure of concentric crater fill glacial remnants.

4.2. Mantle origin

What is mantle material, and how might its deposition and modification relate to “brain terrain”? In the analyzed images, the presence of mantle material at the inner margins of crater walls, and in topographic lows between concentric crater fill ridges, suggests that mantle material could be an atmospherically emplaced, ice-rich deposit, that preferentially accumulates in shadowed areas (Mustard et al., 2001; Hecht, 2002; Head et al., 2003). Surface ages of ~1.5 My suggest that mantle material in Utopia Planitia concentric crater fill craters is temporally associated with recent hemisphere-wide latitude-dependent mantle (LDM) deposition events (Mustard et al., 2001; Head et al., 2003; Kreslavsky and Head, 2006): deposits which are thought to contain sufficient dusty material to generate a surficial lag deposit during sublimation of near-surface ice (Marchant et al., 2002).

4.3. Polygonalized mantle

Seasonal thermal contraction cracking generates contraction-crack polygons in ice-rich sediment on Earth and Mars (Washburn, 1973; Mellon, 1997; Mangold, 2005; Marchant and Head, 2007). As in the formation of “brain terrain,” sublimation may initially be locally enhanced at polygon margins, generating high-center mantle polygons, which may be analogous to terrestrial sublimation polygons (Washburn, 1973; Mellon, 1997; Marchant et al., 2002; Kowalewski et al., 2006; Marchant and Head, 2007). The lack of strongly oriented mantle polygons suggests that young mantle material has not flowed significantly (Zimbelman et al., 1989; Milliken et al., 2003), consistent with thicknesses of <40 m—although a preferred orientation may arise where mantle material overlies sloped crater walls, and where it occurs proximally to well-developed brain terrain. For the latter, contraction cracks may
be aligned with those of nearby or underlying brain terrain. Infilling of polygonal fractures with overlying lag deposit fines could generate subsurface wedges, similar to the initial steps in the formation of “brain terrain.”

As with “brain terrain” discussed earlier, inversion of sublimation-polygon-like topography (polygons with convex-up centers) could occur if sublimation continued to remove near-surface ice at polygon centers, but slowed at polygon troughs due to the presence of thickened accumulations of sediment along polygon troughs (e.g., Marchant et al., 2002). This differential sublimation process could also account for the formation of low-center mantle polygons with relatively flat, low-lying interiors, and elevated margins. This shared inversion process accounts for the similarity in morphology between low-center mantle polygons and open-cell “brain terrain” cells, although open-cell “brain terrain” cells are generally larger than mantle polygons, and form in gradational contacts with closed-cell “brain terrain,” rather than in mantle material.

Across the martian mid-to-high latitudes, low-center polygons are exceptionally uncommon in HiRISE images (Levy et al., 2009), suggesting that unique conditions may exist at the margins of mantle surfaces in concentric crater fill terrains. The concentration of low-center polygons within scalloped depressions in the mantle (that may have a sublimation origin) (Kadish et al., 2008; Zanetti et al., 2008; Lefort et al., 2009), and in regions where the mantle thins and pinches out, suggests that enhanced removal of subsurface ice by locally intense sublimation may be critical for the formation of low-center mantle polygons.

4.4. Climate implications: Local and global

What do the proposed mechanisms for “brain terrain” and mantle formation and modification suggest about climate conditions in Utopia Planitia at $\sim 1.5$ My and $\sim 10–100$ My timescales? Debris-covered glacier-like landforms have been documented extensively in martian mid-latitudes, and have been interpreted to be geomorphic evidence of cold and arid climate conditions, dominated by sublimation of ground ice during periods of low obliquity, and drastic redistribution and deposition of ice on the surface during periods of high obliquity (Mustard et al., 2001; Kreslavsky and Head, 2002, 2006; Laskar et al., 2002, 2004; Head et al., 2003). Glacier-like deformation of thick accumulations of ice-rich material during high-obliquity ($\sim 35–45^\circ$) (Madeleine et al., 2007) redistribution/depositional periods during the past $\sim 10–100$ My may account for the emplacement of concentric crater fill, while more subtle obliquity excursions over the past $\sim 1–2$ My (up to $\sim 35^\circ$) (Head et al., 2003) may account for the emplacement of thinner, static mantle material. Near-surface modification of both “brain terrain” and mantle is consistent with cold and arid climate conditions and sublimation-driven processes. These lines of evidence suggest an Amazonian hydrological cycle dominated by solid-vapor transitions rather than by widespread melting and flow of liquid water.

Recent work (e.g., Soare et al., 2007, 2008) has concluded that widespread melting and thermokarst erosion has been instrumental in the formation of some Utopia Planitia surfaces (e.g., scalloped terrain present in mantle material). What do mantle polygons and
“brain terrain” indicate about the presence and duration of saturated active layers in Utopia Planitia during the recent Amazonian? From terrestrial experience, the formation of low-center polygons on Earth is most dramatic in ice-wedge polygons, which require seasonal input and freezing of liquid water (Washburn, 1973; Root, 1975; Marchant and Head, 2007). However, raised shoul- ders also form on sand-wedge polygons that develop in cold and arid climates in which liquid water is not available in significant quantities (Péwé, 1959; Berg and Black, 1966; Washburn, 1973; Root, 1975; Marchant and Head, 2007). If ephemeral liquid water was present during the development of low-center mantle polyg- ons, driving the formation of pronounced polygon-margin shoul- ders, then its spatial extent was limited to concentrated occur- rences at the tapering margins of the mantle, and to both the floors and steep slopes within scalloped depressions. This range of locations in which low-center mantle polygons are observed is inconsistent with simple ponding and saturation of sediments. Fur- ther, exposures of pristine “brain terrain” in locations where the mantle has been completely removed from the surface strongly suggest a cold and dry (e.g., sublimation) mechanism for the re- moval of mantle material to form windows down to the “brain terrain;” had these pits been water-saturated to form ice-wedge polygons, it is likely that the underlying “brain terrain” would have been reworked and extensively modified. Lastly, the preservation of original “brain terrain” cell axial furrows suggests that subse- quent, widespread cryoturbation has not disrupted these fine-scale surface features. Rather, we suggest that the morphology of “brain terrain” and mantle material can be accounted for by atmospheric deposition of ice during periods of high obliquity, and modific- ation of ice-rich units by a suite of cold-desert processes including glacial deformation, thermal contraction cracking, and differential sublimation in the absence of abundant near-surface liquid water.

Finally, these analyses provide a framework for understanding relationships between “brain terrain” textures present on lobate debris aprons and lineated valley fill elsewhere on Mars and the latitude-dependent mantle (LDM). Contacts between “brain ter- rain” and LDM occur extensively at martian midlatitudes, includ- ing transects in eastern Hellas, Deuteronalit S Mensae and Nilosyrts Mensae (Fig. 21). The wide distribution of contacts between “brain terrain” and LDM material suggests that the transition between mid-Amazonian glacial periods, and more recent Amazonian, dry “periglacial” conditions are not restricted to local occurrences and may indicate global climate processes.

5. Summary and conclusions

“Brain terrain” and polygonally-patterned latitude-dependent mantle (LDM) surfaces were analyzed in Utopia Planitia. Stratigraphic relationships and crater-count ages show that the mantle surface postdates concentric crater fill “brain terrain” by ~10–100 My. Two unique surface textures were identified in each unit, respectively, closed-cell “brain terrain” and open-cell “brain terrain,” and high-center mantle polygons and low-center mantle polyg- ons. Lateral contacts between textures are shown to be gradational, suggesting modification of “brain terrain” and mantle material into the current range of surface morphologies. A com- bined glacial-stress/thermal-contraction and differential sublima- tion mechanism is proposed for the formation and modification of “brain terrain” on concentric crater fill. A similar model, driven by thermal contraction cracking and differential sublimation of under- lying ice, but without glacier-like ice flow, is also proposed for the formation and development of the polygonally patterned mantle. This explanation for examined “brain terrain” and polygonalized mantle material requires two different styles of atmospheric deposi- tion of ice: an older, “glacial” deposition period for the formation of concentric crater fill “brain terrain,” and a more recent “ice age” mantling period for the deposition of LDM. Both deposition styles result in the formation of near-surface excess ice (ice vol- ume exceeding available pore space). Glacier-like concentric crater fill with closed-cell “brain terrain” is interpreted to have formed during a mid-latitude peak-glaciation period that ended at ~10–100 My. This was followed by quiescent cold desert conditions, preceding the most recent “ice age” (Head et al., 2003) period at ~1–2 My, responsible for the deposition of mid-high latitude de- pending mantle material, the formation of mantle polygons, and the modification of closed-cell “brain terrain” present at mantle margins into open-cell “brain terrain.” Understanding the develop- ment of “brain terrain” on Utopia Planitia concentric crater fill provides insight into analysis of “brain terrain” present on lobate debris aprons and lineated valley fill across the martian midlati- tudes, suggesting a dynamic history of ice redistribution under different cold Amazonian conditions during the late Amazonian.

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