Concentric crater fill in the northern mid-latitudes of Mars: Formation processes and relationships to similar landforms of glacial origin

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1. Introduction

Concentrically-lineated, crater-filling deposits (concentric crater fill, or CCF, Fig. 1) have been described at middle-high latitudes on Mars since the Viking era, and have long been associated with a suite of features typical of fretted terrain (e.g., lobate debris aprons, LDA; and lineated valley fill, LVF) (Sharp, 1973; Squyres, 1978, 1979; Malin and Edgett, 2001). Hypotheses explaining the formation of these unusual landforms range from entirely water-free processes (e.g., aeolian fill), to ice-assisted talus creep, to debris-covered glaciers. Based on analysis of new CTX and HiRISE data, we find that concentric crater fill (CCF) is a significant component of Amazonian-aged glacial landsystems on Mars. We present mapping results documenting the nature and extent of CCF along the martian dichotomy boundary over ~30 to 90°E latitude and 20–80°N longitude. On the basis of morphological analysis we classify CCF landforms into “classic” CCF and “low-definition” CCF. Classic CCF is most typical in the middle latitudes of the analysis area (~30–50°N), while a range of deglaciation processes results in the presence of low-definition CCF landforms at higher and lower latitudes. We evaluate formation mechanisms for CCF on the basis of morphological and topographic analyses, and interpret the landforms to be relict debris-covered glaciers, rather than ice-mobilized talus or aeolian units. We examine filled crater depth–diameter ratios and conclude that in many locations, hundreds of meters of ice may still be present under desiccated surficial debris. This conclusion is consistent with the abundance of “ring-mold craters” on CCF surfaces that suggest the presence of near-surface ice. Analysis of breached craters and distal glacial deposits suggests that in some locations, CCF-related ice was once several hundred meters higher than its current level, and has sublimated significantly during the most recent Amazonian. Crater counts on ejecta blankets of filled and unfilled craters suggests that CCF formed most recently between ~60 and 300 Ma, consistent with the formation ages of other martian debris-covered glacial landforms such as lineated valley fill (LVF) and lobate debris aprons (LDA). Morphological analysis of CCF in the vicinity of LVF and LDA suggests that CCF is a part of an integrated LVF/LDA/CCF glacial landsystem. Instances of morphological continuity between CCF, LVF, and LDA are abundant. The presence of formerly more abundant CCF ice, coupled with the integration of CCF into LVF and LDA, suggests the possibility that CCF represents one component of the significant Amazonian mid-latitude glaciation(s) on Mars.

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(2009b) to account for CCF morphology in Utopia Planitia. The potential for the current presence of significant quantities of ice in CCF and LVF was suggested by the documentation of abundant examples of integrated, glacier-like flow features in LVF and LDA across the martian dichotomy boundary (e.g., Head et al., 2006a,b, 2010; Levy et al., 2007; Morgan et al., 2009), the presence of ring-mold craters in LVF/LDA deposits (Kress and Head, 2008), and the discovery of significant volumes of nearly pure ice within lobate debris aprons and lineated valley fill described by Holt et al. (2008) and Plaut et al. (2009) using SHARAD radar data.

Advances in understanding of CCF and related landforms have followed from the improving spatial resolution and coverage of spacecraft data, including image and topographic datasets. Here, we use Context Camera (CTX) (Edgett et al., 2008) and High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2009) image data, coupled with HRSC high-resolution stereo DEMs (Oberst et al., 2005; Jaumann et al., 2007) and supplemented by MOLA topographic data, to address the following outstanding questions related to CCF: (1) What are the morphological characteristics of CCF at high resolution, and what does the morphology suggest about CCF composition? (2) Are there morphological subtypes of CCF, and if so, what is their geographical distribution? (3) If ice is involved in CCF processes, is any still present? (4) What is the relationship between CCF and other crater-filling materials (e.g., dunes) on Mars? (5) What is the relationship between CCF and LVF/LDA? (6) What do relationships between LVF/LDA/CCF processes suggest about the origin and development of martian glacial landforms? We focus on CCF found along the martian dichotomy boundary (particularly within −30 to 90°E and 20–80°N), in the vicinity of a range of landforms that have been interpreted as features of glacial origin.

2. Mapping mid-latitude crater-filling units

Concentric crater fill (CCF) has been classically described in regions containing abundant lineated valley fill (LVF) and/or lobate debris aprons (LDA) as a crater-interior unit characterized by multiple rings or lineations concentric with the crater rim (Squyres, 1979) (Figs. 1a and 2). At Mars Orbiter Camera (MOC) resolution (1.5–20 m/pixel), the surface texture associated with LVF, LDA, and CCF lineations appears mounded and furrowed, a texture described as “brain or corn-like pit and mound textures” (Malin and Edgett, 2001), “pit-and-butte” texture (Mangold, 2003) or
“knobs—brain coral” (Williams, 2006). Detailed analysis of HiRISE images has led to a description of CCF surface texture as “brain coral terrain” (Dobrea et al., 2007) or “brain terrain” (Levy et al., 2009b). For succinctness and consistency, we will refer to this surface texture throughout as “brain terrain.” HiRISE images reveal textural differences between “brain terrain” mounds or “cells”—particularly “closed cells” (arcuate or domed mound features that are commonly ~10–20 m wide, and that may have surface grooves or furrows located near the centerline of the cell’s long axis) and “open cells” (arcuate and cuspate cells that are delimited by a convex-up boundary ridge surrounding a flat-floored depression) (Fig. 2) (Levy et al., 2009b).

Mapping of crater-filling units at martian mid-latitudes can be accomplished using both HiRISE and CTX image data in concert (Fig. 3). Full-resolution CTX data are sufficient to resolve broad-scale ridges and troughs associated with CCF (Fig. 2), while detailed analysis of relationships between “brain terrain” surface textures is facilitated by observation at HiRISE resolution. Full-resolution CTX images spanning Mars Reconnaissance Orbiter orbits 1331–7927 from the study region (~30 to 90°E, 20–80°N) were inspected for the presence of crater-filling units. Crater-fill units from the 1000 images surveyed were mapped on a sinusoidal equal-area global map (Fig. 3).

3. CCF morphological relationships

Having briefly outlined the morphological characteristics of individual CCF deposits, the next step in assessing the origin, development, and modification history of CCF is to document the range of stratigraphic and morphological relationships observed.
between CCF and other martian landforms (e.g., Squyres, 1979; Squyres and Carr, 1986; Levy et al., 2009b). Here, we consider relationships observed between both ice-related landforms (e.g., LVF, LDA) (Squyres, 1979; Lucchitta, 1984; Squyres and Carr, 1986; Head et al., 2006a,b, 2008, 2010; Holt et al., 2008; Levy et al., 2009b; Plaut et al., 2009) and non-ice-related landforms (such as talus, craters, and dunes).

### 3.1. CCF and host craters

Because CCF is a crater-interior unit, relationships between CCF and its host craters can be used to evaluate CCF-forming processes. Analysis of image and topography data indicates that CCF does not merely line or coat the interior of craters; rather it consists of a flat and high (mesa-like) or convex-up surface that fills host craters (Fig. 4). Fill thicknesses can be estimated by comparing predicted crater depths from Garvin et al. (2002) with observed depths from MOLA or HRSC topographic profiles (e.g., Levy et al., 2009b). Six measured fill depths vary from ~600 m to ~1700 m, and commonly constitute ~75% of expected crater depth (Fig. 4).

Contacts between CCF material and crater walls have variable morphology. In some instances, the upper surface of CCF material sits well above the crater wall and is topographically separated from the crater wall by a bounding scarp up to ~100 m high (Fig. 4). In other cases, CCF surfaces grade from sloping crater walls to the CCF surface—this latter relationship is most typical of craters in which abundant latitude-dependent mantle material rings the crater interior (Fig. 2) (Head et al., 2003; Levy et al., 2009b).

In some cases, crater-fill material appears to have cross-cut or transgressed over crater rims (Fig. 5). For example, one crater in
Deuteronomilus Mensae (Fig. 5) shows low-definition CCF within a crater that is connected to degraded “brain terrain” surfaces outside the crater by a series of linear, positive-relief ridges. Similar ridges are present to the east and to the west of the crater. Ridges to the east of the crater extend from a nearby valley floor, upslope and onto the outer walls of the crater rim. HRSC topographic profiles of the deposit suggest that the low-definition CCF material is ~300 m lower within the crater and outside the crater than it is on the rim of the crater (Fig. 5). The ridges are morphologically similar to drop moraines typical of terrestrial glaciers (Marchant et al., 1993; Benn et al., 2003), as well as martian glaciers (Head and Marchant, 2003; Shean et al., 2005) that form as debris is shed at the glacier margins. If this interpretation is correct, it indicates that previously crater-filling material was at least 300 m higher in the past—sufficient to permit flow over the crater rim and onto the valley floor outside of the crater.

Fig. 4. (a) Classic concentric crater fill that is clearly separated from the interior crater wall talus slopes. White line indicates track of topographic profile. Portion of P14_005670_2241. Illumination from left. North to image top. (b) HRSC high-resolution DTM topographic profile across CCF-containing crater. Inset shows calculated depth expected given crater diameter from Garvin et al. (2002) and an idealized bowl-shaped profile.
3.2. CCF and dunes

Zimbelman et al. (1989) hypothesized that CCF is an aeolian feature, primarily on the basis of a layered surface texture visible in Viking images of “classic” CCF terrain; what do high-resolution images suggest about crater-filling aeolian processes (e.g., sediment and dune deposition)? At both high and low latitudes, dunes partially fill some craters (Fig. 6). Dunes are seldom present along the entire interior of a crater, and typically drape, rather than fully fill, the crater interior (Fig. 6). Dune morphology can be readily distinguished from “brain terrain” textures in HiRISE and CTX images, suggesting that CCF is not primarily composed of mobile aeolian material. Rather, higher-resolution image data reveal that the layered surface texture observed in Viking image data (Zimbelman et al., 1989) is a visual effect produced by closely-spaced lineations composed of “brain terrain” surface texture on topographically undulatory CCF ridges (Fig. 2) (Levy et al., 2009b).
3.3. CCF and talus

In CTX and HiRISE images, contacts between CCF and talus slopes are clearly discernable (Fig. 7). Some examples of “low-definition” CCF (e.g., in Deuteronilus Mensae or Arabia Terra, Fig. 7) show that “brain terrain” patterned crater-fill material abuts talus slopes associated with crater rims. The contact between such talus slopes and the CCF is abrupt, with CCF material present downslope along a steep scarp. Such relationships are most clearly visible at low latitudes, where annuli of mantling material are not present at the crater/crater-fill contact (e.g., Fig. 2). Similar contacts between LVF and talus scarps in Nilosyrtis Mensae were interpreted by Levy et al. (2007) as evidence of the recession of LVF surfaces from a previous high-stand. This model suggests that the talus slope was emplaced down to the level of the (previously higher) LVF margin, and remains as a steep talus slope now that the LVF/CCF surface has vertically ablated. In other locations, CCF is topographically separated from the interior slopes of crater walls by tens to hundreds of meters of relief, suggesting that CCF material is physically distinct from talus shed by crater walls (Fig. 4) (Russell et al., 2004; Russell and Head, 2005). Lastly, CCF is present in craters with a range of rim morphologies, ranging from crisp and relatively well-defined (Figs. 1, 2, and 8) to complexly eroded (Fig. 9), suggesting that CCF is not simply composed of mobilized talus shed from crater rims.

3.4. CCF and LVF

CCF and lineated valley fill (LVF) commonly are present in the same geographical areas on Mars (Squyres, 1979; Squyres and Carr, 1986; Head et al., 2006b, 2010). What do contacts between LVF and CCF show? In many locations (Figs. 10 and 11), contacts between CCF and LVF show surficial merging of CCF and LVF lineations. LVF-containing valleys commonly breach craters hosting CCF, both from upslope (Fig. 10) and downslope (Figs. 10 and 11). Merging of surface lineations occurs in both cases (Head et al., 2006a). HiRISE analysis of “brain terrain” surface textures on both CCF and LVF show similar groupings of open and closed cells forming characteristic lineations (Fig. 12). Topographic profiles across LVF/CCF contacts are gradational and smooth in HiRISE image data, and at both MOLA resolution (~460 m/pixel) and HRSC-DTM resolution (~100 m/pixel) (Figs. 10 and 11).
3.5. CCF and LDA

Along with lineated valley fill (LVF), CCF commonly occurs in the same geographical areas as lobate debris aprons (LDA) (Squyres, 1979; Squyres and Carr, 1986; Head et al., 2006b, 2010). In some craters, “brain terrain” surfaced lobes extend from crater walls, towards the crater interior, but do not entirely fill the crater (Fig. 13). Lineations on these lobes are commonly concentric with crater rims. In other craters (Fig. 14), crater-filling material spills from within the crater down to proximal, LVF-surfaced valley floors. Such fill is commonly lineated along strike, rather than concentrically with the crater, similar to lineations in lobate debris aprons (LDA) (Squyres, 1979; Squyres and Carr, 1986; Head et al., 2006a, 2010; Levy et al., 2007).

3.6. CCF and the LDM

What relationships are observed between CCF and the martian latitude-dependent mantle (LDM) (Kreslavsky and Head, 1999, 2000; Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003; Levrard et al., 2004)? Relatively low-albedo mantling material typically overlies some portion of CCF surfaces along the dichotomy boundary (e.g., Fig. 2). This mantling material is commonly polygonally patterned by thermal contraction cracks and ranges in thickness from <1 m to several tens of meters (Levy et al., 2009b). This mantling material overlies CCF “brain terrain” and shows little evidence of deformation associated with CCF flow, consistent with a very youthful age of emplacement (~1–2 Ma), as compared to the more ancient CCF (see below) (Levy et al., 2009b).
4. Age estimates

Crater counting on CCF surfaces poses many of the same challenges as crater counting on LDA and LVF surfaces: small craters are obscured by "brain terrain" cells (Levy et al., 2009b) while larger craters may have undergone a range of modification processes (Mangold, 2003; Kress and Head, 2008). Two principle morphologies of craters are observed on CCF surfaces: fresh, bowl-shaped craters (Fig. 8a and b) and "ring-mold" craters (RMCs) (Fig. 8a and c) that display the same inner ring or inner plateau morphologies described for RMCs on LVF and LDA by Mangold (2003) and Kress and Head (2008). Both fresh and RMC craters are observed on CCF surfaces, suggesting a complex geological history for CCF.

In order to provide an age estimate for the formation of CCF, we avoid counting directly on CCF surfaces. Rather, we identify CTX images in which both filled (CCF) and unfilled craters are present (Fig. 15, Table 1). By counting on the ejecta of these craters, it is possible to bracket the formational period of CCF: the CCF must have formed after the filled-crater ejecta was emplaced, but before the unfilled-crater ejecta was emplaced (Fig. 15). Crater counts were made on 10 impact crater ejecta deposits surrounding comparably-sized craters with and without CCF deposits. The combined crater count results are summarized in Fig. 16. This binned-count approach assumes that CCF deposits formed at approximately the same time throughout the study region. Both counts show significant roll-off at small crater size—in part a resolution effect associated with CTX data and in part due to small-crater resurfacing at high latitudes due to mantle emplacement processes (e.g., Head et al., 2003; Levy et al., 2009a; Kreslavsky, 2009). Still, counts on unfilled-crater ejecta show a quantitatively younger age. Best-fit ages calculated using Hartmann (2005) isochrons and only craters larger than 100 m are ~70 Ma for unfilled craters and ~320 Ma for CCF filled craters; similar to age estimates for LDA and LVF that span ~0.1–1 Ga (Mangold, 2003; Head et al., 2006a,b, 2010; Levy et al., 2007; Kress and Head, 2008). Visual inspection of isochron plots suggest an age for unfilled craters of ~60–80 Ma, with filled craters forming a population of surfaces that may be up to ~1 Ga in age. The kink in the filled crater curve at the ~0.5 km diameter bin may be indicative of an older population of craters that has undergone a range of resurfacing processes (Neukum and Hiller, 1981; Werner, 2009), or the Amazonian filling of considerably older craters. Both curves indicate, however, that CCF formation is a process typical of the relatively recent Amazonian.

5. Discussion

On the basis of the observations presented above, we can evaluate hypotheses regarding the origin and significance of concentric crater fill (CCF). Given the strong morphological dissimilarity between CCF and landforms identified as dunes, we suggest that CCF does not represent a purely aeolian crater-filling process. However, atmospheric processes such as deposition of windblown...
sediment (e.g., Zimbelman et al., 1989) and snow/ice (Head et al., 2006a,b) may be important in CCF formation (see below). Likewise, CCF may be modified by aeolian processes, such as dust-devil redistribution of surface sediment (e.g., van Gasselt et al., 2010, their Fig. 7). Nonetheless, clear morphological differences exist between CCF surface textures and dunes typical of martian low and high latitudes (Fig. 6). Although CCF deposits bear a superficial resemblance to terrestrial seif dunes, dune-fields typically lack the concentric pattern typical of CCF, and do not display open- and closed-cell “brain terrain” morphology (Levy et al., 2009b).

The observation that CCF is commonly elevated above the interior slopes of craters, and in places is markedly convex-up, suggests that CCF is not simply crater rim talus material that has been transported down-slope by ice-assisted creep (e.g., Squyres,
Indeed, CCF is found on craters with well-preserved rims, as well as craters that have eroded rims (Figs. 1, 4 and 8–10 respectively). Two key morphological observations are difficult to reconcile with such a rock-glacier-like mechanism (Haeberli et al., 2006): (1) recession of CCF from high stands (implying the removal of a large volume of excess ice) (Figs. 7 and 2) the presence of convex-up and high-standing CCF in crater interiors (implying preferential removal of CCF material around crater wall interiors) (e.g., Russell et al., 2004; Russell and Head, 2005) (Fig. 4). In both instances, internal rock–rock contact in the rock-glacier model for CCF would provide a uniform surface topography, even as interstitial ice was removed from the valley fill (LVF).
deposit. Rather, these morphological observations suggest that significantly excess ice (ice volume exceeding pore space volume) is required to form CCF.

What does the presence of landforms that have been interpreted as indicators of debris-covered glacial ice in or on CCF deposits suggest about the origin of concentric crater fill? Ring-mold craters (RMCs) have been interpreted as interactions between impactors and near-surface ice through spallation and differential sublimation (Mangold, 2003; Kress and Head, 2008). “Brain terrain” has been interpreted as the surface expression of a multi-stage sublimation process in the upper portions of CCF, LVF, and LDA surfaces, in which fracture and sediment infill drive differential sublimation of buried ice (Levy et al., 2009b). Finally, tracing of surface lineations on LVF, LDA, and CCF shows continuity of flow and folding over multiple-km length-scales, strongly suggesting the internal deformation and flow of an ice-rich substrate forming these landforms (Head et al., 2006a,b, 2010; Levy et al., 2007; Dickson et al., 2008; Morgan et al., 2009). Indeed, the presence of topographic ridges and troughs, as well as fractures (both thermal-contraction-driven and resulting from structural failure of deforming ice) are typical for terrestrial debris-covered glaciers, and may form parallel or orthogonal to the flow direction (Marchant et al., 2002; Head et al., 2006a,b; Levy et al., 2007). The combined observation of ring-mold craters, “brain terrain,” and flow-related lineations on CCF all suggest that CCF is composed largely of debris-covered ice that underwent flow and has been modified by sublimation. We interpret CCF to represent crater-interior debris-covered glaciers (e.g., Garvin et al., 2006; Kreslavsky

Fig. 12. Comparison of similar “brain terrain” surface textures on CCF (b) and LVF (c). (a) Context image showing CCF integrated with LVF (see Fig. 11). Illumination from the left. North to image top. (b) Typical CCF “brain terrain.” Illumination from image bottom. Portion of PSP_008296_2175. (c) Typical LVF “brain terrain.” Illumination from image bottom. Portion of PSP_009588_2175.

Fig. 13. Partial fill of a crater by lobe-like, rim-concentric, “brain terrain” surfaced deposits. The partial fill material is similar in position and morphology to lobate debris aprons observed elsewhere on Mars. Illumination from left. Portion of P16_007242_2159.

Fig. 14. Lobate debris apron-like flow emerging from a crater and integrating into LVF. This feature suggests a similar origin for CCF, LVF, and LDA. Illumination from left. North to image top. Portion of P04_002442_2221.
What is the relationship between CCF and other martian glacial landforms, such as LVF and LDA? The morphological similarity between "brain terrain" surfaces associated with LDA, CCF, and LVF suggest that these units have undergone similar developmental histories. The confluence and merging of CCF, LVF, and LDA lineations suggests that they have similar rheological properties and were active during the same period. The comparable crater retention ages recorded by CCF, LVF, and LDA suggest that similar processes were involved in the formation and modification of these units, over the course of the recent Amazonian. A large body of evidence suggests that LVF and LDA formed as debris-covered glaciers as ice accumulated at high obliquity in protected alcoves along dichotomy boundary slopes, flowed as cold-based glaciers, and eventually sublimated as climate conditions grew colder and/or drier (Forget et al., 2006; Head et al., 2006a,b, 2010; Levy et al., 2007; Dickson et al., 2008; Madeleine et al., 2009). Morphological similarities between CCF and LVF/LDA suggest that similar mechanisms may have controlled CCF formation and development. Given (1) the detection of buried ice beneath martian LDA and LVF (Holt et al., 2008; Plaut et al., 2009), (2) the thinness of overlying sublimation residue deposits suggested by the presence of ring-mold craters (Mangold, 2003; Kress and Head, 2008), and (3) the hundreds to thousands of meters of fill material still present in CCF deposits, we suggest that CCF may represent a significant reservoir of non-polar martian ice, extending over ~38,000 km² along the martian dichotomy boundary.

What does CCF morphology indicate about changes in CCF volume over time? The presence of steep talus slopes above some CCF deposits (e.g., Fig. 7) suggests that in places at least tens of meters of CCF material has been removed since the cessation of flow. At a larger scale, the presence of "uphill flowing" low-definition CCF deposits (Fig. 5), similar to perched glacier deposits observed in Coloe Fossae crater interiors (e.g., Dickson et al., 2008, 2009), suggests that in places at least 300 m of CCF material has been removed. The vertical drop-down of CCF surfaces is consistent with loss of relatively clean glacier ice (Marchant et al., 2002, 2007; Kowalewski et al., 2006; Marchant and Head, 2007), and is inconsistent with loss of pore ice in grain-supported regolith (e.g., rock-glaciers would not result in a change in surface elevation). This suggests that CCF deposits were once considerably more voluminous than is indicated by their current extent. For many CCF deposits, the presence of an additional 300 m of material would over-fill the craters that the CCF currently occupy, suggesting along with the presence of breached CCF craters (e.g., Figs. 5 and 10–12), the intriguing possibility that CCF deposits were once part of a larger, inter-crater glacial landsystem (Marchant and Head, 2008, 2009), remnants of which are preserved as CCF, LVF, and LDA deposits, along with ice buried beneath mid-latitude pedestal craters (Kadish et al., 2008). If this were the case, then the current extent of CCF represents only the fraction of the maximum extent of ice that has been preserved beneath a debris cover as the glaciation waned.

Finally, what is the relationship between CCF and the martian latitude-dependent mantle (LDM) (Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003; Levrard et al., 2004)? The difference in age between LVF/LDA/CCF and the LDM by one to two orders of magnitude suggests that they represent distinct periods of ice deposition on Mars that have left a record of unique characteristics. Young, meters-thick LDM deposits drape CCF, LVF, and LDA deposits, along with ice buried beneath mid-latitude pedestal craters (Kadish et al., 2008). If this were the case, then the current extent of CCF represents only the fraction of the maximum extent of ice that has been preserved beneath a debris cover as the glaciation waned.

Fig. 15. Filled and unfilled craters provide a means of estimating the age of CCF emplacement. The most recent CCF emplacement period must be older than the age determined by counts on unfilled-crater ejecta and younger than the age determined by counts on filled-crater ejecta. Illumination from upper left. North to image upper right. Portion of P06_003272_2079.

Fig. 16. Crater counts for ejecta of CCF filled craters (white circles) and unfilled craters (black circles). Best-fit ages are ~60 Ma for unfilled craters and ~300 Ma for filled craters, suggesting that CCF formed during the recent Amazonian.

Table 1
Index of craters used for crater retention age dating.

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latitude-dependent LDM emplacement may represent a transition from more active glacial periods to a more quiescent “ice age” period of martian climate evolution (e.g., Head et al., 2003; Levy et al., 2009b).

6. Conclusions

On the basis of morphological analyses of concentric crater fill (CCF) along the martian dichotomy boundary, we conclude that a debris-covered glacier-like formation mechanism is the most consistent explanation for the current distribution and characteristics of CCF, rather than ice-mobilized talus creep or purely aeolian processes. Given strong morphological similarities between surface textures associated with CCF, LVL, and LDA, we suggest that similar debris-covered glacier processes account for the formation of all three landforms. Filled crater depth–diameter analysis indicates that in many locations, hundreds of meters of ice may still be present under descised surficial debris. Analysis of breached CCF-containing craters suggests that in at least several locations, CCF-related ice was once several hundred meters higher than its current level, and has sublimated significantly during the most recent Amazonian (between ~60 and 300 Ma). The presence of formerly more abundant CCF ice, coupled with the integration of CCF into LVL and LDA glacial landforms suggests the possibility that CCF represents one component of a significant, Amazonian-age glaciation of mid-latitude Mars.

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