Middle to Late Amazonian tropical mountain glaciers on Mars: The ages of the Tharsis Montes fan-shaped deposits

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ABSTRACT

Fan-shaped deposits (FSDs) extending to the northwest of the Tharsis Montes on Mars are the remnants of Amazonian-aged, cold-based, tropical mountain glaciers. We use high-resolution images to perform new impact crater size-frequency distribution (CSFD) analyses on these deposits in an effort to constrain the timing and duration of ice accumulation at tropical latitudes on Mars. This analysis revises the current understanding of the chronology regarding the formation of the glaciers and of the ridged facies in the Arsia Mons deposit, a deposit interpreted to be formed from recessional cold-based drop moraines. We develop a conceptual model that illustrates the effect of moving glacial ice on superposed impact craters of various sizes, including the buffering of underlying geologic units from impacts caused by the presence of the ice for extended periods of time, and the interpretation of crater retention ages of the subsequent glacial deposits following the periods of active glaciation. The new CSFD analyses establish best-fit crater retention ages for each entire Tharsis Montes FSD; these are ~220 Ma for the Ascraeus FSD at 8.35° S, ~125 Ma for the Pavonis FSD at 1.48° N, and ~210 Ma for the Arsia FSD at 11.92° N. Because the age for each deposit represents a combination of the stratigraphically older ridged facies and the younger knobby and smooth facies, the crater retention ages are most likely to represent dates subsequent to the onset of glaciation and prior to its final cessation. Estimates of the time necessary to build the deposits using net accumulation rates from atmospheric general circulation models and emplacement rates from glacial flow models suggest durations of ~45–150 Ma, depending on the specific obliquity history. These surface crater retention ages and related age estimates require that massive volumes of ice (on the order of 105 km3) were emplaced at tropical latitudes on Mars during the Middle to Late Amazonian. Additionally, we determined CSFD ages of three adjacent drop moraine units at Arsia Mons (725 Ma, 475 Ma and 345 Ma) and used these to calculate the average amount of time needed to form one of the approximately 185 drop moraines forming these deposits; we found that a typical drop moraine formation time in the Arsia FSD ridged facies to be on the order of ~106 years. These formation ages are considerably longer than that required for typical moraine systems alongside dynamic, wet-based glaciers on Earth, but are in approximate accord with recent geomorphological and geochemical data that document long-term, ice-margin stability for several cold-based glaciers in interior Antarctica. The difference in the ages of the ridged facies and non-ridged portion of the Arsia FSD suggests that the tropical mountain glaciers may have been emplaced over a period spanning many hundreds of millions of years. CSFD measurements for lava flows predating and postdating the Arsia Mons FSD suggest a maximum possible age of <750 Ma and a minimum age for the late stage, post FSD lava flows of ~105 Ma. Together, this evidence supports a scenario in which ice has been present and stable in substantial quantities (~105–106 km3) at tropical latitudes during extended periods of the Middle to Late Amazonian history of Mars. This implies that during this time, Mars sustained periods of spin-axis obliquity in the vicinity of 45°, during which time polar ice deposits were substantially reduced in volume or perhaps even absent.

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1. Introduction

The detailed nature of recent, largely obliquity-driven (Laskar et al., 2004), climate change on Mars has become more clear as evidence mounts for a variety of Amazonian-aged, ice-rich, surface
features at mid and low latitudes (e.g. Boynton et al., 2002; Head et al., 2003, 2006; Head and Marchant, 2003, 2008; Shean et al., 2005, 2007; Levy et al. 2007; Kadish et al., 2008; Baker et al., 2010). The current presence of polar ice caps on Mars (e.g. Phillips et al., 2008) with minimal quantities of surface ice at low latitudes (Head and Marchant, 2008) suggest a complex exchange of volatiles over the past few hundred Ma (e.g. Tanaka, 2000). In an effort to constrain the timing of ice accumulation at tropical latitudes (~25°N to 25°S latitude), we use recently acquired high-resolution images to perform new and revised crater counting analyses on the fan-shaped deposits (FSDs; Zimbelman and Edgett, 1992) extending to the northwest of the flanks of each volcano. These new ages are 220 Ma for Ascreaus Mons, 210 Ma for Arsia Mons, and 125 Ma for Pavonis Mons. The data rollover at diameters of less than 700 m.

Following the recognition and documentation of these tropical mountain glaciers, Forget et al. (2006) used a general circulation model to show that ice/snow will accumulate on the western flanks of the Tharsis Montes during periods of high obliquity (>45°), reproducing the distribution of the Tharsis Montes FSDs remarkably well. The net accumulation rate estimates from the Forget et al. (2006) GCMs were then used in conjunction with ice-sheet flow models (Fastook et al., 2008) to reproduce possible histories for the growth and retreat of the glaciers. Estimates of the time necessary to build the deposits suggest durations of ~45–150 Ma, depending on the speciﬁc obliquity history. Here, we use the surface ages of the entire FSDs as well as the ages of sections of the ridged facies derived in this study to update our understanding of when ice was emplaced at tropical latitudes during the Amazonian.

2. The ages of the Tharsis Montes fan-shaped deposits

Relative ages of the Tharsis Montes and Olympus Mons (Fig. 1a) have been previously established using both stratigraphic relationships and crater counting. Based on their observations and the resulting paleostratigraphic reconstruction, Scott and Tanaka...
(1981) argued that the Tharsis Montes FSDs are approximately the same age as the youngest flows coming from each of the volcanoes. In accordance with Viking data and stratigraphic observations, Tanaka (1986) assigned the Tharsis Montes FSDs Late Amazonian ages. Subsequent mapping has been conducted (e.g. Scott and Zimbelman, 1995; Scott et al., 1998) which verifies that the FSDs were emplaced throughout the Middle to Late Amazonian. In order to determine absolute ages, crater-counting techniques have been used to date the Tharsis Montes and their respective FSDs (Shean et al., 2005, 2006; Kadish et al., 2008), as well as Olympus Mons (e.g. Basilevsky et al., 2005; Hartmann and Neukum, 2001; Head et al., 2005). In this section, we discuss revised absolute ages for each of the Tharsis Montes FSDs, on Ascaerus, Pavonis and Arsia Mons. All best-fit ages calculated in this study are derived from the isochrons defined by Hartmann (2005).

2.1. Ascaerus Mons

Kadish et al. (2008) undertook an analysis of the impact crater size-frequency distribution over a near-complete (>99% coverage) THEMIS IR mosaic (100 m/pixel) of the ~13,000 km² Ascaerus Mons FSD. These images were supported by a partial THEMIS VIS mosaic (18 m/pixel) that covered 83% of the FSD. Only craters that were too small to be seen in the IR data were counted using the VIS data, although the diameters of the larger craters were checked using the VIS data. Craters were counted down to 350 m in the IR mosaic. Plotting the VIS and IR craters on the same isochrons showed that the data flattened out for diameters less than 350 m, crossing the isochrons (Hartmann, 2005). This implies that the deposit has undergone modification and possible resurfacing since its deposition; the flattening of the plot at low diameters suggests that craters <350 m in diameter are being eroded or infilled at the same rate that they are being produced. Because of this, Kadish et al. (2008) used craters that had diameters >500 m in order to calculate an absolute crater retention age. The data from N(0.5) to N(2) yielded a best-fit age of approximately 250 Ma.

We have recounted the craters in the Ascaerus Mons FSD (Fig. 1b) using newly available CTX images (6 m/pixel), which provide 100% coverage of the deposit. This revision allowed us to improve the accuracy of previous diameter measurements, include new craters, and exclude craters that are clearly parts of secondary chains. When plotted on the isochrons, the new crater counts show that the data roll over at craters <700 m in diameter (Fig. 1b). Using the data from N(0.7) to N(2), which includes 14 craters, provides a revised best-fit age of 220 Ma, which is 12% younger than the previous calculation by Kadish et al. (2008). This updated age brings it closer to the ages of the Arsia and Pavonis FSDs.

2.2. Pavonis Mons

Shean et al. (2005) used THEMIS IR and VIS data to establish a Late Amazonian age for the ~74,000 km² Pavonis Mons FSD, between 10 Ma and 200 Ma based on isochrons from Hartmann and Neukum (2001). Plotting their data on the Hartmann (2005) isochrons produces a best-fit age of approximately 110 Ma. They note, however, that limited coverage of the area and a poor statistical distribution make this absolute age somewhat uncertain; a young crater-retention age is expected due to (1) modification of the units of the FSD since their deposition and (2) erosion and infilling of smaller craters (Shean et al., 2005). Additionally, some craters observed may be impacts into the Tharsis lava plains, which underlie the FSD units; counting these craters would result in an overestimate of the age (Shean et al., 2005).

In a manner similar to the Ascaerus revision discussed above, we utilized CTX images which provide 100% coverage of the FSD that were obtained and released since the Shean et al. (2005) study. The new crater counts (Fig. 1d) confirm that, similar to the Ascaerus FSD, craters ~700 m in diameter are being eroded at a rate comparable to the rate at which they are forming, resulting in a roll over of the data on the size-frequency distribution; this erosion is likely to be eolian in nature, and smaller craters may also be completely infilled by the thick regional dust deposits (e.g. Christensen, 1986) and the contributions of tephra, fine-grained explosive volcanic eruption products from the Tharsis Montes (Wilson and Head, 2009). Using the 49 craters counted from N (0.7) to N(4) yields a revised best-fit age of 125 Ma (Fig. 1d). This new age is 14% older than the Shean et al. (2005) calculation.

2.3. Arsia Mons

Using THEMIS VIS and HRSC images, Shean et al. (2006) concluded that a Middle to Late Amazonian age for the ~166,000 km² Arsia Mons FSD is the most likely. They calculated a lower boundary for the absolute age of >25 Ma (90% confidence) by counting only the fresh craters on the deposit and an upper boundary of <650 Ma (90% confidence) by counting all craters on the deposit. This upper boundary population included craters that had experienced infilling and modification, indicating that they were either older than the FSD deposit or emplaced on an underlying flow (Shean et al., 2006). Plotting the Shean et al. (2006) data of all craters >700 m in diameter within the FSD on Hartmann (2005) isochrons yields a best-fit age of approximately 175 Ma.

Using a combination of HRSC and CTX data, we created a seamless mosaic of the Arsia FSD at 10 m/pixel resolution. Counting on this mosaic, we identified 65 craters that are >700 m in diameter, 12 more than were found in the Shean et al. (2006) survey. Plotting the new catalog of 764 craters in the Arsia FSD >250 m in diameter (Fig. 1c) confirms that the rollover in the data occurs at a crater diameter of ~700 m, making this the appropriate lower limit cut off for establishing an absolute age. The resulting best-fit age from the new data, using N(0.7)–N(10), is Late Amazonian, 210 Ma, which is 20% older than the Shean et al. (2006) best-fit age. Using CSFD measurements for lava flows predating and postdating the Arsia Mons FSD, Shean et al. (2006) assigned a maximum possible age of <750 Ma (99% confidence) (the pre-FSD volcanic substrate) and an estimated minimum age for the late stage, post FSD lava flows of ~105 Ma.

3. Age of the Arsia ridged facies

In addition to dating the entire Arsia FSD, we also calculated the ages of three distinct sections of the ridged facies (Fig. 2). Because the Arsia FSD contains the largest sequence of ridges of any of the tropical mountain FSDs, it is the ideal candidate for identifying potential trends in the progression of the ages of the recessional drop moraines as a function of radial distance from the flank of the edifice. Dating an individual ridge is not possible due to the low crater density in the area and the extremely narrow width of each ridge. However, by dividing the ridges into sections, starting with the most distal parts of the FSD from the edifice summit, we can create countable areas and establish a sequence of ages. These ages can then be used to provide clues as to when and how quickly the glacier receded and to assess fluctuations during this period.

Using the revised crater database for the Arsia deposit, we defined three sections of ridges using the most prominent continuous ridges and their stratigraphic relationships as the basis for subdivision (Fig. 2a); we refer to the sections as the outer (farthest from the mountain), middle, and inner (closest to the mountain)
sections. It is important to note that, because the regions were defined based on specific geomorphic and stratigraphic boundaries, they are not all the same size, nor do they contain the same number of ridges. Because the age determination via crater counting accounts for the area of the dated surface, the differences in the areas (in km²) of the sections do not affect the chronology. Although individual ridges can merge or suddenly disappear (as is typical of drop moraines from cold-based ice; Marchant and Head, 2010), we were able to count the number of ridges in each section along multiple radial crossings to provide robust values. We found that the outer, middle, and inner sections contained approximately 80 ridges, 40 ridges, and 65 ridges, respectively. Although we display all craters larger than 90 m in the size-frequency distributions from these ridged areas (Fig. 2b–d), there is a clear rollover in the data for craters < 700 m. This is expected given that our dating of the entire FSDs also showed that the crater populations did not match the expected production functions for craters < 700 m. As such, only craters > 700 m in diameter were used to calculate best-fit ages for the ridged sections. The results show best fit ages of 725 Ma for the outer section (Fig. 2b), 475 Ma for the middle section (Fig. 2c), and 345 Ma for the inner section (Fig. 2d). This chronology confirms that the ridges are the oldest facies within the FSDs. Further, within the ridge facies, the outer ridges are the oldest and the inner ridges are the youngest; this suggests that the ridges reflect overall ice retreat, though the possibility for ice-front fluctuations during overall ice recession remains. In addition, the time that elapsed between the formation of each section suggests that an individual ridge may take hundreds of thousands or even a few million years to form. In the following paragraphs, we explore the possible timing of ridge formation.

**Fig. 2.** (A) A CTX and HRSC mosaic of the Arsia Mons fan-shaped deposit. The ridged sections (outer, middle, and inner) have been mapped in blue, green, and yellow, respectively. These boundaries between these sections were defined on the basis of particularly large, continuous ridges. The ridges in the inner section are discontinuous, resulting in an area that is not contiguous. At their widest extents, the outer, middle, and inner regions have 80 ridges, 40 ridges, and 65 ridges, respectively. Because ridges merge and can be buried, ridges were counted across multiple transects. (B)–(D) Crater size-frequency distributions for the outer, middle, and inner ridged sections in the Arsia Mons fan-shaped deposit, with best-fit ages of 725 Ma, 475 Ma, and 345 Ma, respectively. The data roll over at diameters less than 700 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The location of the ridges at the distal margin of the FSD makes them less likely to show the effects of artificially young ages due to covering by glacial ice. It should be noted, however, that the glacier is likely to have fluctuated/pulsated as it retreated (Fastook et al., 2008). As such, we cannot definitively state that the outer section of ridges took 250 Ma to form (the difference between the ages of the outer and middle ridged sections). However, because the ages suggest that the entire sequence occurred over hundreds of millions of years and produced almost 200 ridges, we can use the differences in ages and the number of ridges in each section to calculate first order estimates for the amount of time necessary to produce a single typical ridge. Taking the ratio of the time periods for each section (250 Ma, 130 Ma, and 215 Ma) to the number of respective ridges in each section (80 ridges, 40 ridges, and 65 ridges) produces strikingly consistent values for the average amount of time needed to form a ridge (3.13 Ma/ridge, 3.25 Ma/ridge, and 3.31 Ma/ridge).

To assess the plausibility of a million-year-timescale of ridge formation, we performed a 1D calculation of the debris thickness superposed on the glacier (supraglacial debris) that would be necessary to form a ridge given the cross-sectional area of a ridge, the glacial flow rate, and the time allowed to form the ridge (Fig. 3 and Table 1). Supraglacial debris is considered to be primarily volcanic ash and dust because the glacier is cold-based (Head and Marchant, 2003), eruptions are known to be contemporaneous with the presence of the deposit (Scott and Tanaka, 1981; Tanaka, 1986; Zimbelman and Edgett, 1992), volcanic ash is thought to be common (Wilson and Head, 2009), and scarps of sufficient topographic prominence to produce rockfall are uncommon (Shean et al., 2005, 2007). This model assumes that debris is emplaced along a line extending radially away from the flank of Arsia, and that it is being transported along the surface to the terminus of the glacier, where it is deposited to form a ridge, which has a triangular cross section (Fig. 3). We made this calculation for a minimum, median, and maximum sized ridge and solved for first-order thickness of supraglacial debris along an ice flowline to the ridge (Fig. 3). It is important to note that the ridge cross-sectional area is directly proportional to debris thickness. As such, even if the ridges are ice-cored (perhaps as much as 60% pure ice), the effect will be negligible, as we are concerned with orders of magnitude estimates for the debris thickness. For example, an ice-cored moraine composed of a 60% ice core by volume will still require 40% ash. In order to estimate the effect of time on moraine formation, we ran our model using four different time periods, 1 ka, 10 ka, 100 ka, and 1 Ma. Finally, we applied two possible glaciflow rates (0.01 m/a and 0.1 m/a) to account for the range of values predicted by the glacial models of Fastook et al. (2008). It should be noted that the resulting values for the debris thickness are time-averaged; we would expect this thickness to fluctuate considerably during the extent of its emplacement.

This set of variables (Fig. 3) produces 24 outcomes for the supraglacial debris thickness, ranging from 5 mm to 9 km (Table 1). If we examine the eight possible outcomes for a typical (median) ridge, the range is 8 cm–800 m. As mentioned, some time periods may produce anomalously large debris quantities, especially during massive volcanic eruptions (Wilson and Head, 2009), but these time-averaged values must have been physically possible for tens to hundreds of millions of years to form the entire

Table 1

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<tr>
<th>Ridge cross-sectional area (m²)</th>
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Fig. 3. A schematic diagram showing the key elements of our 1D model for ridge formation. This illustrates the set of variables considered in the model (ridge cross-sectional area, glacial surface flow rate, and formation timescale). The cross-sectional area of the ridge is divided by the formation timescale to derive a debris flux; the supraglacial debris is likely to have been sourced from volcanic eruptions. The supraglacial debris flux is then divided by the glacial surface flow rate to derive a time-averaged thickness of debris necessary to form the moraine.
extensive sequence of ridges. If we consider typical eruption fluxes (e.g. Wilson et al., 2001) and the limitations imposed by the maximum fluxes allowed without completely melting the glacier (Wilson and Head, 2009), it is clear that debris thicknesses on the order of 1 m or larger, which would have to have been sustained for thousands of years, are extremely unlikely. Even under the fast glacial flow scenario (0.1 m/yr), building a typical ridge in 10 ka would require supraglacial debris with a debris thickness of 8 m. Allowing 100 ka to form the ridge requires supraglacial debris with a thickness of 0.8 m, which is still quite high given the time period for which it must have been present. Consequently, the results of this model (Table 1) strongly support a million-year formation timescale for typical ridges. On the basis of the presence of a total of ∼185 ridges in the three ridged subunits of the Arsia Mons FSD (Fig. 2), this individual ridge formation timescale would imply a total duration to form all of the ridges on the order of ∼185 million years.

4. Discussion

The crater retention ages of the FSDs (Fig. 1), and related estimates of the time of emplacement and duration of the TMGs, have important implications for when ice was present in the equatorial regions of Mars. These crater retention ages, however, are derived from the total superposed crater population and entire surface area within each FSD. We know, based on our dating of the Arsia ridged sections (Fig. 2), that the facies are not all the same age; the distribution of craters within the Arsia FSD suggests that the ridged section is the oldest region, with younger surfaces exposed in the inner parts of the FSD. For example, a crater size-frequency distribution plot for the Arsia FSD excluding the ridged facies yields a best-fit age of approximately 130 Ma, which is 80 Ma younger than the age derived for the whole deposit. Other young surfaces have been dated within the FSDs, as shown in work by Shean et al. (2007); their results show evidence for more recent small-scale glaciations occurring in graben on the western flank of Arsia. In this case, the fill material left by the accumulation of ice is calculated to be ∼35–115 Ma, with a model age of 65 Ma (Shean et al., 2007). In addition, at the Pavonis FSD, Shean et al. (2005) identified a smooth facies that may represent debris-covered ice, implying that some glacial remnants are still present at these low latitude regions (see also Head and Marchant, 2007).

A conceptual model provides a useful basis on which to visualize and interpret the complex relationships between the cold-based glacial history of the tropical mountain glaciers and the chronologies indicated by superposed impact crater size-frequency distributions (Fig. 4). We subdivided this illustration into three sequential steps: (1) an active glacier at maximum advance; (2) a period when the glacier partially retreats leaving drop moraines (the ridged facies; during this period, the glacier can advance and retreat several times, leaving multiple, overlapping drop moraines, as is the case for Arsia Mons); and (3) a period when the ice sheet collapses, forming the knobby and smooth facies.

Period 1: An active glacier at maximum advance (Fig. 4a): An active glacier forms on the northwest flank of the Tharsis Montes and extends to its maximum distance of advance. The existing lava flows beyond the ice margin have a CSFD coincident with the number of craters accumulated on the unit or flow surface since the initial emplacement of the lava flow unit. Craters continue to form and accumulate on all surfaces and are preserved on the lava flows. On the moving glacial ice, however, impact craters less than about 10 km will not excavate down to the base of the substrate, and thus will be carried forward along the ablation zone and lost. Craters larger than this will penetrate to the base of the ice sheet but will produce craters with unusual residual substrate morphologies, if they are recognizable at all. Craters beneath the glacier will not be modified because the glacier is cold-based. Thus, as long as the ice sheet is present, no craters except very large ones will leave evidence of their formation.

Period 2: The glacier retreats, leaving drop moraines (Fig. 4b): The active glacier retreats and leaves a series of drop moraines. Retreat of glacier ice exposes an underlying surface whose craters formed prior to ice advance and have not been eroded beneath cold-based glacier ice. Subsequent accumulation of new craters is now possible in the drop-moraine region. Assessment of the ages of the ridged facies must distinguish between relatively old craters formed prior to glacier advance, and those formed since ice retreat. A CSFD for those craters formed subsequent to glacier retreat would represent a crater retention age for this part of the ridged facies. New craters forming on the glacial ice will not be preserved below a critical diameter, a value dependent on the new thickness of the ice sheet. During this period, the glacier might advance and retreat multiple times, leaving superposed drop moraines, or might retreat, reach stability for a period of time, and then retreat again, leaving multiple, parallel drop moraines. Similar suites of drop moraines, produced over million-year timescales, have been documented for several outlet glaciers in East Antarctica.
Period 3: Ice sheet collapse (Fig. 4c): The ice sheet collapses, leaving the outer drop-moraine facies intact, and producing an intermediate knobby terrain facies (due to vertical downwasting of the ice sheet) and an inner smooth facies (formed by the last alpine glacial ice remnants) (Head and Marchant, 2003). The knobby and smooth facies now begin to undergo crater accumulation. Depending on the thickness of the knobby and smooth-facies deposits, pre-glacial craters formed on the top of the underlying lava flows may be visible and must be distinguished from craters formed in the post-ice-sheet collapse period in order to obtain a correct age for the ice sheet collapse.

The CSFD of craters superposed on the knobby and smooth facies is a crater retention age that dates the time of glacial collapse and loss of the ice sheet. In principle, the age of the ridged facies is also an indication of the time elapsed since the beginning of its retreat. If the ridged facies represents the initial retreat of the glacier, and the knobby/smooth facies the final collapse of the ice sheet, then the difference between these two ages represents the time between the beginning of the retreat and the final collapse.

Much of the debris that is left following the collapse of the glacier is fine-grained volcanic tephra and atmospheric dust, and is highly mobile. This means that many craters in the knobby facies will be modified and destroyed with time, further altering, and making younger, the crater retention age of this part of the deposit. Since the knobby facies comprises the majority of the deposit area, this would have a significant effect on attempts to date both the collapse of the glacier, and the duration of its presence.

Due to the cold-based nature of these tropical mountain glaciers (e.g. Head and Marchant, 2003; Kadish et al., 2008; Shean et al., 2005), it is difficult to discern how many distinct glaciations have occurred. Confirmed observations of superposed, crisscrossing and merging moraines could either reflect modest ice-sheet fluctuations during a single glaciation, or even multiple glaciations. Despite this complication, the young ages of the FSDs are extremely important because they ensure at the very least that ice has been present in the equatorial region during the Middle to Late Amazonian. The morphological observations of the ridges and their interpreted timescales, as well as the presence of several inward facing scarps representing margins of lava flows chilled against the ice (Shean et al., 2005; Kadish et al., 2008), support the interpretation that the glaciers have experienced significant oscillations between advance and retreat (see also Fastook et al., 2008).

5. Conclusions

Our analysis of the Tharsis Montes fan-shaped deposits (FSDs) (Fig. 1) has yielded revised ages and a new understanding of the chronology regarding the formation of the ridged facies in the Arisia FSD. The updated crater-count data establishes best-fit crater retention ages of 220 Ma for the Ascaraeus FSD, 125 Ma for the Pavonis FSD, and 210 Ma for the Arisia FSD (Fig. 1b–d). Further, our crater count analysis and 1D model calculation of the average amount of time needed to form a typical drop moraine in the Arisia ridged facies (on the order of 105 years) implies that during tropical mountain glacial periods in the Middle to Late Amazonian, ice maintained near-maximum extents for tens to hundreds of millions of years, and that initial retreat was slow. Such long-term, ice-margin stability is inconsistent with dynamic, wet-based glaciation, but is in approximate accord with some cold-based glaciers in Antarctica, which on the basis of geomorphological data and cosmogenic-nuclide dating of moraines show significant ice-marginal fluctuations over million-year time scales (Brook et al., 1993; Marchant et al., 1993; Staiger et al., 2006; Swanger et al., 2011). Furthermore, the consistent width, continuity and parallelism of the drop moraines on Arisia Mons implies relative climate stability during these periods. Finally, the difference in ages between the outer ridged section (725 Ma) and the non-ridged knobby-smooth facies of the Arisia FSD (130 Ma) suggests that TMG's have been present for hundreds of millions of years in order to create the observed differences in crater density. This evidence collectively suggests a scenario in which ice has been and stable in substantial quantities (~1010–1011 km3) at tropical latitudes during extended periods of the Middle to Late Amazonian, implying sustained periods of spin-axis obliquity in the vicinity of 45°. These volumes approach those of the current polar ice deposits (Zuber et al., 1998; Plaut et al., 2007) suggesting that during periods of tropical mountain glaciation, polar ice deposits were substantially reduced in volume or perhaps even absent.

Acknowledgements

The authors would like to thank the HiRISE, CTX, and HRSC teams, without whom this study could not have been completed. The authors are grateful for financial support from NASA Mars Climate Dynamics Program (DCMP) grant NNX09A1HG to JWH, and to the Jet Propulsion Laboratory (JPL 1237163) supporting membership on the Mars Express High-Resolution Stereo Camera (HRSC) Team. We gratefully acknowledge National Science Foundation Grant PLR-0944702 “Quantifying Surface Processes above Buried Ice in Antarctica: Implications for Terrestrial Climate Change and Glaciation on Mars” to DRM and JWH.

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