MID-LATITUDE AMAZONIAN GLACIATION ON MARS: CONTROLS ON ACCUMULATION AND GLACIAL FLOW PATTERNS. James L. Fastook[1] and James W. Head[2], [1]University of Maine, Orono, ME 04469, fastook@maine.edu, [2]Brown University, Providence, RI 02912.

Introduction: A wide range of evidence shows that the current distribution of ice on the surface is anomalous, and that the Amazonian period was characterized by a variety of non-polar ice-related deposits ranging from *high-latitude* mantles, to *mid-latitude* lobate debris aprons, lineated valley fill, concentric crater fill, and pedestal craters, to *low-latitude* tropical mountain glaciers [1-3]. General circulation models (GCM) and glacial flow models illustrate the orbital parameter and atmospheric/surface conditions under which periods of glaciation are favored [e.g., 4-5], and the resulting patterns of accumulation of snow and the flow of ice [6-8]. Geological observations and impact crater size-frequency distribution data strongly suggest that during the Late Amazonian, a significant part of the mid-to-high latitudes in both hemispheres was covered by regional snow and ice deposits (preserved today beneath pedestal craters [9-11]) and that local depressions (primarily impact craters) were the sites of significant ice accumulation, and preservation beneath a residual debris cover (concentric crater fill (CCF) [12-13]). Pedestal crater (Pd) heights show that a significant amount of snow and ice accumulated in the mid-to-high latitudes during these periods (regionally the mean height is ~50 m, but values up to 160 m are seen in Utopia [14]). Accumulations in CCF are typically many hundreds of meters [12-13] and can exceed several kilometers [12-13], filling the crater completely. Could these landforms signify a sufficient thickness of ice to produce active glaciers that flowed across the surface, filling existing lows such as impact craters?

We explore the nature of regional ice accumulation and glaciation during this time period and address the following questions: 1) What thickness is required to initiate ice flow on a flat, inter-crater area under Late Amazonian conditions? 2) Could the current Pd mean thickness value (~50 m) be the remnant of equilibrium flow (that is, did thicker ice flow until it reached an equilibrium thickness similar to the current observed Pd thickness)? 3) What slopes *are* required to initiate ice flow under Late Amazonian conditions and where is this most likely to occur geologically? 4) What was the nature of ice cover and glaciation during periods of maximum ice accumulation in the late Amazonian?

Thickness required to initiate ice flow: Velocity is obtained by integrating strain rates through the vertical, with strain rates related to stresses through the Flow Law with a temperature-dependent rate factor. Figure 1 shows $\log_{10}$ of the flow velocity as a function of ice thickness and surface slope for a temperature of 215 K. Clearly low surface slopes (~1°) typical of the flat inter-crater terrain require considerable thickness (800-1000 m) to initiate flow. Only for considerably larger surface slopes (>5°) is there any significant flow for 200 m. Even at slopes as high as 20°, 50 m only yields 0.3 mm/yr. A temperature of 225 K increases all velocities by a factor of 4, reducing the threshold for 200 m to 3.5°. A further increase to 235 K reduces the necessary slope to 2.2°, but 100 m thick ice still requires >5° to generate 1 mm/yr.

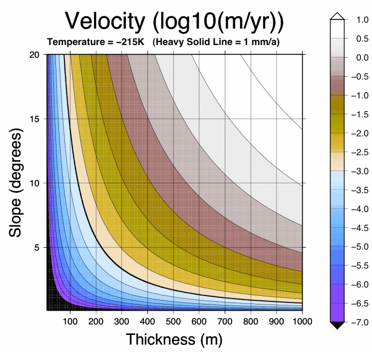

Figure 1: Flow velocity ($\log_{10}$(m/yr)) as a function of ice thickness (m) and surface slope (degrees) for a temperature of 215 K with the heavy solid line indicating a velocity of 1 mm/yr.

Could the current Pd mean thickness value be the remnant of equilibrium flow?: Was the Pd layer the last phase of a thick persistent ice sheet that reached a configuration that supported flow? Or was it a transient, relatively thin ice-rich layer that deformed as it covered and flowed into the crater depressions?

Evidence exists for the latter case in the form of Pd, perched craters, and excess-ejecta craters described in detail in [9-11]. These three types of craters relate to the impacts into an ice-rich layer that is at most a few hundred meters thick. Each type reflects differing degrees of penetration, followed by complete sublimation of any un-armored regions of the ice complex.

Repeated deposition and removal of this thin layer is suggested in that ~80 m height difference is observed between two Pds 20 km apart. In addition, 30 have superimposed Pds. For this to occur, the first Pd would have to form, the entire ice-rich layer outside the armored zone would have to be removed, a second ice-rich layer would have to reform, and the superimposed Pd could then be emplaced. Clearly this requires that there be multiple episodes of ice-rich layer cover. GCM results [4-5] predict ice accumulations as high as 10 mm/yr during periods of high obliquity exactly in the mid-high latitudes where these craters occur.

One might ask why the transient layer never gets any thicker than the 50-160 m suggested by the Pds, since GCM results suggest this layer could form in as little as 20 Kyr, a time much shorter than the duration of the obliquity excusions. Estimates of the volume of the Pd-defined layer [9-12] are close to the known volumes of the polar caps that are the source of moisture for the high-obliquity mid-high latitude precipitation. The transient layer is "supply-limited" in that when the cap

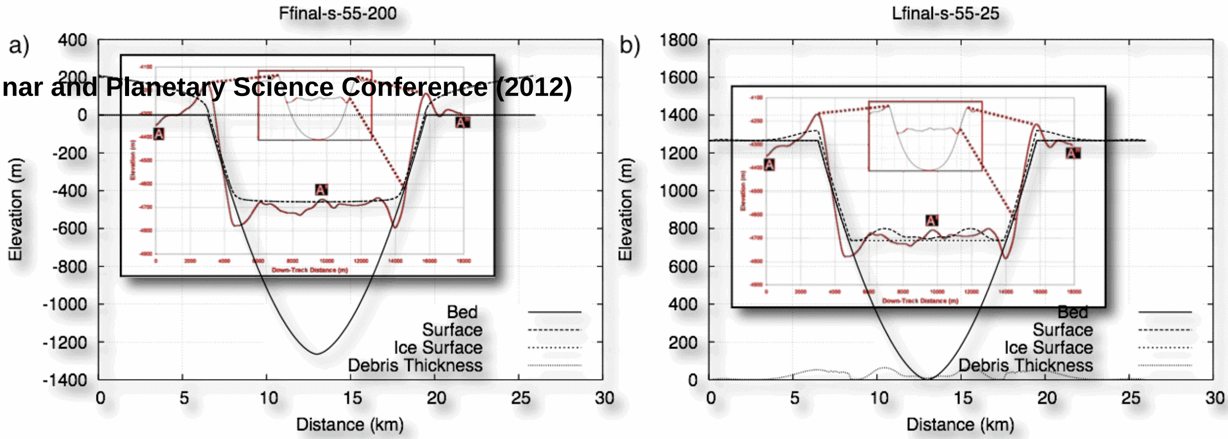

Figure 2: a) Comparison between simulated crater filling from persistent 200 m layer and CCF-containing crater (red, P14 006570_2241 [17]) after 450 Myr, b) simulated crater driven by 301003BIN_A_P001_N obliquity solution [13] and the same CCf-containing crater.

is exhausted, the source is removed, and deposition ceases even if the obliquity is still high.

What slopes are required to initiate ice flow under Late Amazonian conditions and where should this occur geologically?: Evidence exists for a widespread transient ice-rich layer 50 to a few hundreds of m thick in the mid-high latitudes where GCM results deposit ice at high obliquity. How does this thin layer become the several-hundred-meters- to kilometers-thick deposit observed as CCF? As we described, significant flow of thin ice at Amazonian temperatures can only occur for relatively steep slopes. Garvin et al. [15] show that crater-wall slopes correlate strongly with crater size, with slopes from 10-30^o. Figure 1 shows that these slopes would easily provide significant flow, even for layers < 200 m.

A transient layer uniformly blankets the terrain and flow down the steep walls into the crater interior thickens the deposit there, which is then less likely to completely sublimate during the next episode of low obliquity. Also the re-exposed crater walls provide a source of debris that can armor the crater-interior ice surface, adding to its likelihood of surviving until the next cycle of high obliquity. Layer formation and removal must happen many times, with the layer repeatedly forming, flowing, and sublimating away. In the obliquity-driven movement of water to and from the mid-high latitudes, a small amount is deposited in the crater depressions in each cycle, accumulated there by flow down the steep slopes of the crater walls.

What was the nature of snow and ice cover and glaciation during periods of maximum ice accumulation in the late Amazonian?: For this we turn to a 1D flowband model [6, 16, 17], coupled with debris transport. As the ice surface drops below the rim of the crater, debris is deposited on the ice and transported forward with the flowing ice.

We first perform an experiment to see how long it takes for the crater to fill to a level that matches an observed CCF crater (P14_006570_2241 [18]). We begin with a uniform thickness (200 m) and hold fixed the boundary thickness. A comparison between the model results (black) and the observed CCF crater profile (red) is shown in Figure 2a. It takes 450 Myr for the model crater to fill to the level in the CCF crater.

Next we subject this ice sheet/debris model to a climate driven by an obliquity scenario [13] with repeated cycles of ice-layer formation during the time when the Pds formed. We chose an obliquity threshold of 35^o, above which we have a positive mass balance (1 mm/yr), and below which we ablate the ice. We limit the deposited layer to the specified thickness by turning off the precipitation when the layer volume has reached a "supply-limited" value. Even at cold temperatures ice is transported into the crater, resulting in thicker ice there and thinner ice on the slopes and inter-crater terrain. With negative SMB, not all of the ice in the crater may be removed and the crater can fill with ice and transported debris. In addition we can reduce the negative SMB as the debris layer armors the ice beneath it. The start-and-stop nature of the forward motion of the ice dictates that the transported debris layer will not be uniform in thickness and it can form concentric ridges similar to those observed in the CCF. These can be seen in Figure 2b. Note the ripples match the scale and amplitude of the observed surface.

Conclusions: Pds provide us with a means of estimating the thickness of the ice layer that periodically mantled the mid-high latitudes during the Amazonian. Focusing on the CCF as an example of a glacial landform, we demonstrate that flow from an inter-crater terrain ice-rich layer can fill the craters in 450 Myr. We then show how a cyclical pattern of recurring layers, driven by an obliquity solution, can fill the craters with a significant volume of ice as well as transport debris from the crater walls out into the central regions of the craters. The cyclical pattern of the mantling layers results in a pattern of surface debris in the craters that is compatible with the appearance of the CCF.

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