Carbon Dioxide Glaciers on Mars. J. L. Fastook[1] and J. W. Head[2], [1]University of Maine, Orono, ME, 04469, USA, fastook@maine.edu, [2]Brown University, Providence, RI, 02912, USA, James_Head@Brown.edu.

Introduction: The presense of carbon dioxide glaciers on Mars is one possible explanation for high latitude glacier (HLG) features such as those shown in Figure 1 **[1]**. These overlapping loop-like features consist of small ridges. Several have been described by **[2,3]** and are difficult to explain if they consist of regular water ice. Ridges are typically 15-80 m wide, seem not to have modified the underlying deposits, occasionally cross each other, and appear to be relatively young in age. **[2]** suggested that they resembled drop moraines observed at the stable margins of a cold-based terrestrial glaciers. Their overlap suggests that there were multiple episodes of advance to each stillstand where the glacier could convey surface debris to build the moraine. Estimates of the thickness of the glacier that formed the ridges is difficult, but [1] reports evidence for at least 400 m for one inside a crater that was deflected around the crater's central peak. Although similar in scale to lobate debris aprons (LDA) that are thought to consist of water ice, these HLG features are much more lobate, have lower driving stress, and the material that formed them appears to be completely gone. All evidence points to the fact that the HLG features were formed by a material with a weaker rheology than water ice, and **[1]** suggests CO_2 as a possibility. **[4]** discusses atmospheric collapse during periods of low obliquity **[5]** when CO_2 freezes out onto steep pole-facing slopes at high latitudes. Such low-obliquity excursions last typically 110 ka, and repeat consistently during the last 3 million years, yielding a possible time scale for the HLG formation.

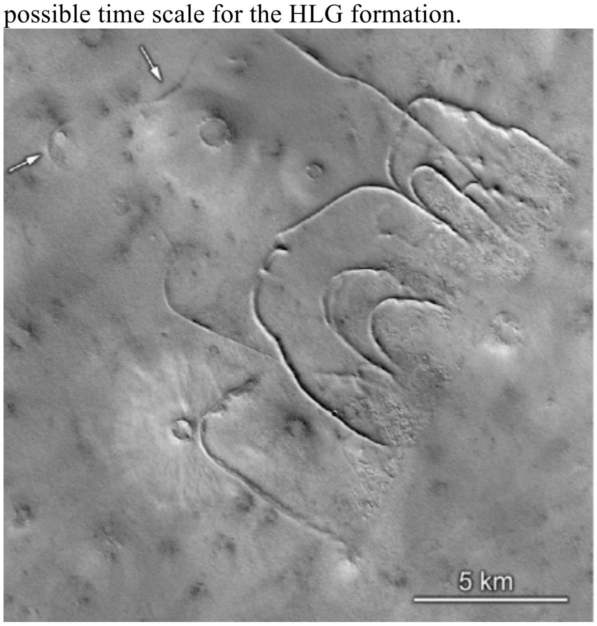

Figure 1: High-latitude glacier (HLG) deposits at 74°N96°E. from CTX image P16_007357_2541 [1, Figure 1].

[1] speculates CO_2 as the material comprising the HGL, and made order-of-magnitude estimates of flow velocities based on a CO_2 rheology by **[6]** and demonstrated that CO_2 was indeed soft enough at the low temperatures of the low-obiquity excusions to have flowed far enough and fast enough to have formed the lobate features associated with the HLG. We have adapted the Mars UMISM model **[7-12]** for this rheology and present results quantifying thicknesses and velocities that would be observed on various sloping beds.

Results: First we consider an ice sheet forming on a uniform flat bed. We prescibe a spatially symmetric mass balance defined by a parabolic form with an accululation area with a peak accumulation rate of 1 cm/yr, declining in either direction to zero and then on into ablation regions. Ice sheets formed by such a static mass balance pattern reach equilibrium in under 100 ka, growing initially within the accumulation region, and then advancing into the ablation zone until net mass balance for the whole ice sheet is zero. Figure 2 shows mass balance, thickness, velocity, and driving stress for a 200 km wide accumulation area.

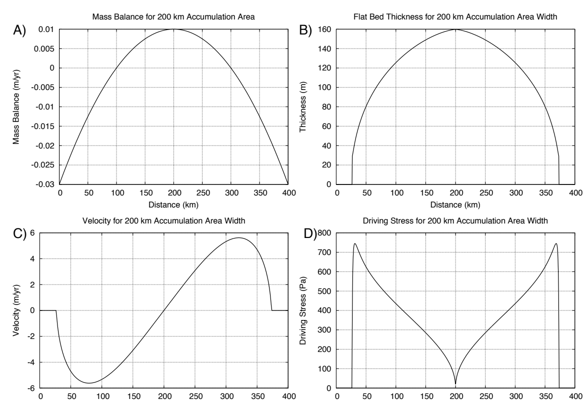

Figure 2: A) Mass balance, B) thickness, C) velocity, and D) driving stress for 200 km wide accumulation area.

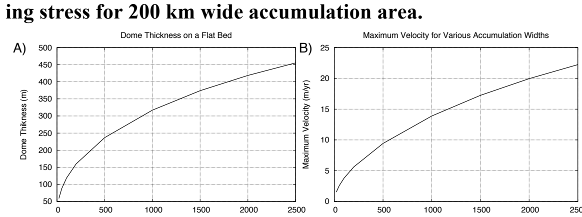

Figure 3: A) Maximum thickness and B) maximum velocity for various accumulation area widths.

Figure 3 shows maximum thickness and velocity for the flat-bed case. Thickness increases with increasing accumulation area width. However, even for our widest accumulation area of 2500 km that produces an equilibrium ice sheet over 4000 km wide, dome thickness barely exceeds 450 m. CO_2 ice is soft, even at the low temperatures encountered during low-obliquity atmospheric collapse.

Having determined the maximum thicknesses we might achieve with CO_2 glaciers of various extents, we then looked at how such ice sheets might behave on a sloping topography. Even the slightest sloping bed contributes to the driving stress, increasing velocity, and hence producing thinner ice sheets for the same mass balance input. Figure 4 shows maximum thickness and velocity as a function of overall slope angle. Note the range of angles is very small, only 0.1^o at the maximum, yet even this small slope reduces thickness by 60%, from 236 m for the flat bed, to 93 m for 0.1^o. Such thinner ice passing the same flux (or more, since the flow is no longer symmetric) of course requires higher velocities, with nearly a quadrupling of the peak velocity.

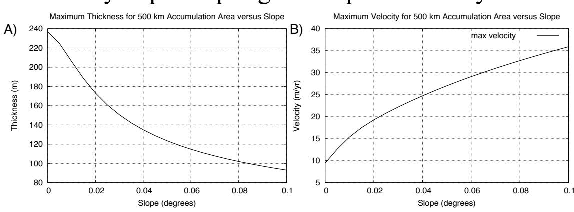

Figure 4: A) Maximum thickness and B) maximum velocity for various overall bed slopes.

Representative profiles with their companion sloping beds (flat, 0.05, and 0.1^o) are shown in Figure 5.

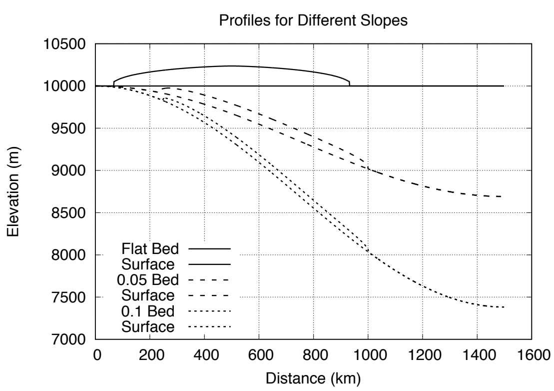

Figure 5: Profiles showing bed and surface for flat, 0.05^o, and 0.1^o.

[4] found that CO_2 accumulated mainly of steep, pole-facing slopes at high latitudes. As such, the long flowlines and large accumulation areas in the previous discussion may not be representative. A profile across a 27 km crater (Tooting Crater, 23.4N, 207.5E) provides a setting to investigate CO_2 deposited on the steep side of a crater. Using a similar parabolic mass balance distribution, this time with ablation limited to 1 cm/yr, CO_2 ice is deposited on slopes that reach more that 25^o. The resulting glacier advances quickly, reaching an equilibrium configuration after less than 10 ka. Figure 6 shows A) the bed and ice surface profiles (solid and dashed line, very close together due to thinness), B) the thickness, less than 30 m maximum, C) the applied mass balance, positive from 7.5 to 17.5 km, with a peak at 12.5 km, and D) velocity, largest at more than 3 m/yr over the steepest part of the slope.

Conclusions: CO_2 glaciers provide a reasonable explanation of observed HLG features. Given the soft rheology of CO_2 at low-obliquity temperatures, they are able to form and flow to reach an equilibrium configuration in a relatively short time (10-100 ka), commensurate with the amount of time available in the low-obliquity excursions.

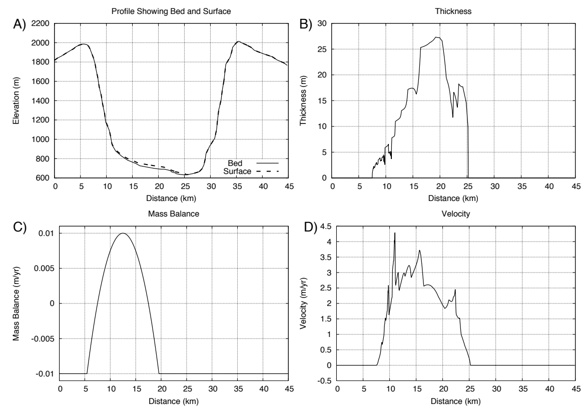

Figure 6: A) Bed and surace profiles, B) thickness, C) mass balance, and D) velocity for a representative crater geometry.

Given their thinness, there is little likelihood of the base reaching the CO_2 frost point, and as such their imprint should be that of a cold-based glacier, with few traces except the moraine, produced as surface debris is carried forward by the movement of the ice. The mass of the current 6 mb atmosphere is $2.5X10^{16}$ kg, and if all the CO_2 were frozen out, would consitute a volume of $1.6X10^4$ km^3, which, if distributed with an average thickness of 100 m would cover $1.5X10^5$ km^2 (a circular ice sheet 440 km in diameter). This area is the order of the observed CO_2 deposits.

References: [1] Kreslavsky and Head, Carbon dioxide glaciers on Mars: Products of recent low obliquity epochs(?). Icarus, 216:111–115, 2011. **[2]** Garvin, Head, Marchant, Kreslavsky, High-latitude cold-based glacial deposits on Mars: Multiple superposed drop moraines in a crater interior at 70_N latitude. Meteorit. Planet. Sci. 41, 1659–1674, 2006. **[3]** Kreslavsky, Head, Unusual glacial-like features in the high-arctic of Mars. Lunar Planet. Sci. XXXVIII, #1576, 2007. **[4]** Kreslavsky and Head. Mars at very low obliquity: Atmospheric collapse and the fate of volatiles. Geophysical Research Letters, 32(L12202), 2005. **[5]** Laskar, Correia, Gastineau, Joutel, Levrard, Robutel, Long term evolution and chaotic diffusion of the insolation quantities of Mars. Icarus 170, 343–364, 2004. **[6]** Durham, Kirby, Stern, Steady-state flow of solid CO2: Preliminary results. Geophys. Res. Lett. 26, 3493–3496, 1999. **[7]** Fastook and Head. Amazonian mid- to high-latitude glaciation on Mars: Supply-limited ice sources, ice accumulation patterns, and concentric crater fill glacial flow and ice sequestration. Planetary and Space Science, 91:60–76, 2014. **[8]** Fastook and Head. Glaciation in the Late Noachian Icy Highlands: Ice accumulation, distribution, flow rates, basal melting and topdown melting rates and patterns. Planetary and Space Science, 106:82–98, 2015. **[9]** Fastook, Head, Forget, Madeleine, and Marchant. Evidence for Amazonian northern mid-latitude regional glacial landsystems on Mars: Glacial flow models using GCM-driven climate results and comparisons to geological observations. Icarus, 216:23–39, 2011. **[10]** Fastook, Head, and Marchant. Formation of Lobate Debris Aprons on Mars: Assessment of regional ice sheet collapse and debris-cover armoring. Icarus, 228:54–63, 2013. **[11]** Fastook, Head, Marchant, and Forget. Tropical mountain glaciers on Mars: Altitude-dependence of ice accumulation, accumulation conditions, formation times, glacier dynamics, and implications for planetary spin-axis/orbital history. Icarus, 198:305–317, 2008. **[12]** Fastook, Head, Marchant, Forget, and Madeleine. Early Mars climate near the Noachian-Hesperian boundary: Independent evidence for cold conditions from basal melting of the South Polar Ice Sheet (Dorsa Argentea Formation) and implications for valley network formation. Icarus, 219:25–40, 2012.