LATE NOACHIAN ICY HIGHLANDS ICE FLOW SYNTHESIS. 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.

Introduction: The record of non-polar ice deposits throughout the Amazonian suggests a cold and dry climate not significantly different from the present climate observed on Mars [1], where latitudinal movement of ice is in response to the varying obliquity component of the spin-axis/orbital parameters [2].

Looking into the Noachian, the record is less clear and characterization of the early climate less certain. The existence of liquid water that flowed across the surface [3-6] as well as open- and closed-basin lakes [7] has lead many to suggest that early Mars was "warm and wet" with pluvial activity [8-15]. Others argue that the early climate was more likely to have been colder and drier [16,17] based on evidence that includes phyllosilicate formation mechanisms [18], low erosion rates [19], poorly-integrated valley networks with the open-basin lakes [20], as well as the possibility that most precipitation might have been nivial [21]. However, little geomorphic evidence for typical wet-based glacial landforms (e.g., drumlins, eskers, etc.) dating from the Noachian has been cited. The existence of a late-Noachian south circumpolar ice sheet [22], for which modeling studies suggest a mean-annual temperature well below freezing [23], also argues for a "cold and icy" early climate. Terrestrial analogs from the Antarctic Dry Valleys demonstrate that fluvial activity can take place at mean annual temperatures well below freezing [24-26]. Recent estimates of the rate of water lost to space [27] have reduced the amount of water available for a "wet" Mars, and evidence from a martian meteorite requiring lower atmospheric pressures [28], when coupled with the faint young Sun, makes it very difficult for atmospheric modelers to produce a "warm and wet" early Mars [29]. "Extreme" events such as meteorite impacts have been proposed, whereby an ephemeral "steam" atmosphere lasting a few thousand years might exist and produce the observed landforms [30-32], however, landform evolution modeling seems to contradict these findings [33].

Recent atmospheric modeling results [34,35] demonstrate that moderate atmospheric pressures, accompanied by a full water cycle, produce a Late Noachian atmosphere where temperature declines with elevation following an adiabatic lapse rate, unlike the current situation where temperature is almost completely determined by latitude. Lower temperatures at higher elevations encourage the movement of water from the "warmer" lowlands to the colder southern highlands, where it is sequestered in the form of regional ice sheets above an ice stability line (ISL) that occurs close to 1000 m elevation. The hydrological system is thus globally horizontally stratified [36], with a global permafrost layer separating the surface from vertical integration and communication with any deeper groundwater. Furthermore, the horizontally stratified hydrologic system in the Late Noachian Icy Highlands means that water migrates from the lowlands to the highlands, precipitates, and accumulates as snow and ice in a "one-way" direction. Once water in the lowlands is exhausted, the hydrological cycle becomes "dormant" until the system is activated by some source of melting (top-down or bottom-up), and meltwater drains to the lowlands to temporarily renew the cycle. Thus, this ice, effectively "stored" at higher elevations, might then be released by "extreme" events, such as meteorite impacts or volcanism, without the need to invoke a "steam" atmosphere. Further geological implications of this "cold and icy" scenario are explored in [25,26] who suggest that meltwater produced seasonally during these episodes might flow naturally toward the lowlands in the areas where the geologic record requires liquid water to be present and flowing across the landscape. As the climate cooled again, water frozen below the ISL would sublime and return to the highlands as snowfall [21,35].

Results: We investigated the character of an ice sheet that is predicted to have formed in the Late Noachian Icy Highlands (LNIH) climate scenario in the highlands (Figure 1), using a range of available moisture supply and different geothermal fluxes. In particular we examined three features of ice sheets that leave a lasting impact on the landscape after the ice sheets are removed: 1) where and how extensively is the bed melted, 2) where and how rapidly is the ice flowing, and 3) are the ice sheets candidates for meltwater production of sufficient volume under known top-down melting scenarios to account for the observed fluvial and lacustrine features? All of these features of ice sheets leave characteristic deposits and features detectable from orbit (e.g., [39]). We analyze the nature and development of the "Late Noachian icy highlands" using glacial flow models and address the following questions:

1. *What is the available reservoir of surface and near-surface water?*: On the basis of the uncertainty in this value for Late Noachian Mars, we adopted a LN surface/near-surface water budget of from ~1X to 20X the current value estimated by [40] (1X = ~30 m GEL, ~5 x 10^6 km^3).

2. *What is the areal distribution of snow and ice?*: The ice was very widespread and relatively evenly distributed above the Wordsworth et al. [35] ISL altitude estimated at +1 km.

3. *What is its average ice thickness and thickness distribution?*: On the basis of the most plausible Late Noachian water budgets (<5X current) and under nominal LN climate conditions, the icy highlands surface ice cover is predicted to be predominantly less than a few hundred meters thick.

4. *Is the ice wet-based or cold-based, and if wet-*

based, in what locations?: Availability of a water supply comparable to the present surface/near-surface volume (1X; [40]) produces no melted bed, even in deep craters. At higher values of available ice (2X to 5X), ice is uniformly cold-based. Only in the most extreme cases of unreasonably large supply volumes and high geothermal heat flux are widespread wet bed conditions observed within the model results. Under supply-limited (<5X) mean LN geothermal gradient conditions, ice accumulation is insufficient to produce basal melting except very locally. In these cases, where ice thickness exceeds 2 km (commonly at the bottom of the deepest impact craters), some basal melting may occur, and potentially produce subglacial lakes. This extensive ice cover also provides an opportunity for the interaction of ascending and erupting magma with the overlying ice, potentially leading to phreatomagmatic eruptions, localized melting and temporary local wet-based glacial conditions (e.g., [41-44]).

5. *What are the flow rates of the ice?*: Velocities in the low-to-moderate supply cases are generally minimal (<a few cm to mm/a), much lower than ice flow velocities on Earth, except in extreme cold-based glacial conditions such as the upland stable zone of the McMurdo Dry Valleys (see [24]).

6. *What are the regional patterns of ice flow (equilibrium ice sheet or local topography dominated)?*: The thin ice (the order of hundreds of meters) and low flow velocities produce a disorganized flow pattern that follows topographic slopes, unlike the pattern of radial flow typical of an equilibrium ice sheet.

7. *What are the predictions for resulting glacial and periglacial landforms that might be recognized in the geological record?*: Late Noachian glacial activity is unlikely to produce and preserve an array of distinctive wet-based glacial and periglacial landforms [39]. Flow rates are so low that cold-based drop moraines [24] might also be inhibited from forming.

8. *What is the most likely volume of the available Late Noachian reservoir of surface and near-surface water?*: On the basis of our analyses and the lack of evidence for widespread wet-based glaciation in the Noachain, we infer that the Late Noachian surface/near-surface ice budget is very likely to be less than 5X the current value (see [40] for discussion).

9. *Could the glacial deposits be a source of meltwater for the observed fluvial and lacustrine features?*: If one applies top-down melting to the Late Noachian Icy Highlands, significant volumes of meltwater can be generated over short time scales. Two scenarios are explored here, one involving a 2000 year period of moderately higher temperatures, and the other a single year of much higher temperatures. For the 2000-year climate excursion, temperature warming of +18 K produces 0.45 Mkm^3, an amount close to our minimum target volume of 0.42 Mkm^3 (the total volume of water in the population of open-basin lakes measured by [7]). In the second scenario, raising surface temperatures to 273 K for a single Mars summer is predicted to produce between 0.15 and 0.4 Mkm^3, depending on whether the PDD factor used was for snow or for ice. This single summer phase of heating melts between 4 and 11 m of the upper ice deposits, close to our minimum target volume. Thus, this top-down single-summer melting of the ice deposit produces between 3 and 10 km^3 of meltwater per km of ice-sheet margin length, comparable to 0.6% to 1.5% of the total ice deposit.

Conclusion: In summary, the Late Noachian Icy Highlands model provides a huge reservoir of glacial ice, and under several plausible top-down melting scenarios serves as a ready source for abundant and volumetrically significant meltwater that could form the observed valley networks and open/closed-basin lakes.

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