LATE NOACHIAN GLACIATION IN THE MARTIAN HIGHLANDS: GLACIAL FLOW MODELING TESTS OF HYPOTHESES. 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: Geological evidence for rainfall, runoff, fluvial and lacustrine activity in the Noachian of Mars (valley networks, lakes and a possible ocean) has been interpreted to mean that the ambient Noachian Mars climate was 'warm/wet-warm/arid' with MAT in excess of 273 K **[1]**. Climate models **[2, 3]** on the other hand, taking into account the 'faint young Sun' and the 'adiabatic cooling effect' (ACE) accompanying a denser atmosphere, predict that the ambient climate had a MAT of ~226 K and that due to the ACE, Noachian Mars would be characterized by 'icy highlands', with significant accumulation of snow and ice in the highlands and accompanying glacial processes (the LNIH model). Investigation of the icy highland model using glacial flow models **[4]** suggest that, given the likely LN water budget **[5]**, LNIH glaciation would be cold-based. Testing the LNIH model has been hampered by the fact that cold-based glaciation, in which glacial ice is welded to the underling permafrost, leaves little to no geomorphic evidence **[6]**.

Recently, results of geological mapping of the Terra Sabaea region of the Circum-Hellas Noachian Highlands has been interpreted to show extensive evidence for the presence of features related to LN-EH glaciation **[7,8]**.

Bouquety et al. **[7]** undertook an analysis seeking geomorphologic evidence for highlands glacial landscapes that might represent an early cold and icy climate, studying the morphometric properties of martian valleys in the southern part of Terra Sabaea. Among these, they interpreted 100 cirques and 83 glacial valleys that have the same morphometric characteristics and trends as terrestrial and martian glacial valleys and glacial cirques, and differ from those observed in fluvial valleys on Earth and on Mars. Identified glacial landscapes are restricted to elevations >1000 m. Bouquety et al. **[7]** proposed that the LN-EH climate was characterized by glaciated highlands at elevations >1500 m; at lower elevations (where fluvial valley network are located), the climate was more temperate allowing liquid water to be stable.

In a followon study, Bouquety et al. **[8]** employed similar methods to search for additional evidence for glaciation in Terra Sabaea, identifying an additional 81 glacial valleys and possible evidence for a former plateau ice cap at the highest elevation in Terra Sabaea; however, evidence for associated glacial cirques was absent. The additional 81 long glacial valleys radiate from an extensive flat plateau, which they interpreted to mark the former presence of a plateau ice cap, an interpretation strengthened by terrestrial analogs. On the basis of these data and interpretations, Bouquety et al. **[8]** proposed a polythermal regime: the plateau ice cap was cold-based except at the margins, where the regime becomes wet-based due to steeper topography that created basal shear stress/heating sufficient to induce melting and form the outlet glacial valleys. They point to the presence of an open-basin paleolake at the transition between inlet glacial valleys upstream and an outlet V-shaped valley downstream, indicating that liquid water played a role in the formation of the Terra Sabaea landscape.

If this interpretation **[7-.8]** is correct, then these features supply important information on the nature of the ambient LN climate and its evolution. In this contribution, we tentatively adopt the interpretation of **[7-8]** and use ice accumulations and glacial flow modeling **[8-13]** to explore its implications for the Late Noachian ambient climate. We ask the following questions:

1) Is the configuration proposed by **[7-8]** plausible with general ice accumulation and glacial flow models?

2) What are the predictions and implications of this interpretation **[7-8]** and the configuration of snow and ice, the Equilibrium Line Altitude ELA), and the position of melting?

3) Does this configuration **[7-8]** represent the ambient climate or a temporary/transitional climate?

4) Is this interpretation **[7-8]** most consistent with a 'warm/wet-warm/arid' or a 'Late Noachian Icy Highlands' ambient climate model?

5) Do our glacial flow model approach and results provide any insights into the validity or further applicability of the **[7-8]** interpretation.

Approach and Analysis: Using UMISM, a finite-element shallow-ice model adapted for Mars **[4, 9-13]**, that requires as input topography (from MOLA **[14]** 0.03125-degree resolution topography, meg0031t.grd), mean annual surface temperatures, annual mass balance, and geothermal heat flux (20 mW/m^2). Output consists of ice thicknesses, column-averaged velocities, and 3D temperature within the ice (from which basal melt rates are calculated when the bed reaches the melting point).

In an attempt to distinguish between the 'warm/wet-warm/arid' and 'cold/arid' LNIH climate hypotheses, we employ two MAT cases, one with 270 K and a second with 226 K. In each case we specify an equilibrium line altitude (ELA), above which mass balance is positive (uniform 0.001 m/yr) and below which it is negative (-0.01 m/yr). Figure 1, with thickness and surface for both cases, shows this with a red outline. Bouquety **[7]** estimated the ELA from one valley and obtained a value of 2556 m. We found that this yielded a much larger ice cap than was indicated by the transitions from U-shaped to V-shaped VN that surround the proposed ice cap. We found the best agreement to their footprint with an ELA of 2800 m. This small ice cap equilibrates quite quickly (approximately 300,000 years for the 270 K case and 700,000 years for the 226 K case). No basal melting was observed in the MAT 226K case, with a maximum ice thickness of 882 m (average 382 m) and velocity as high as 146 mm/yr (but with the majority less than 50 mm/yr). the areal footprint is 15,800 km^2 and the total volume is 6040 km^3. The much warmer, and hence softer, 270 K case produces melting over approximately 4.5% of its area, shown in Figure 1 C,D as white and blue outlining approximately 700 km^2. Maximum thickness is reduced to 355 m (average 131 m) and total volume is 2050 km^3, approximately 1/3rd the 226 K case. Maximum velocity observed over one of the melted bed areas reached 900 mm/yr (but with the majority less than 200 mm/yr).

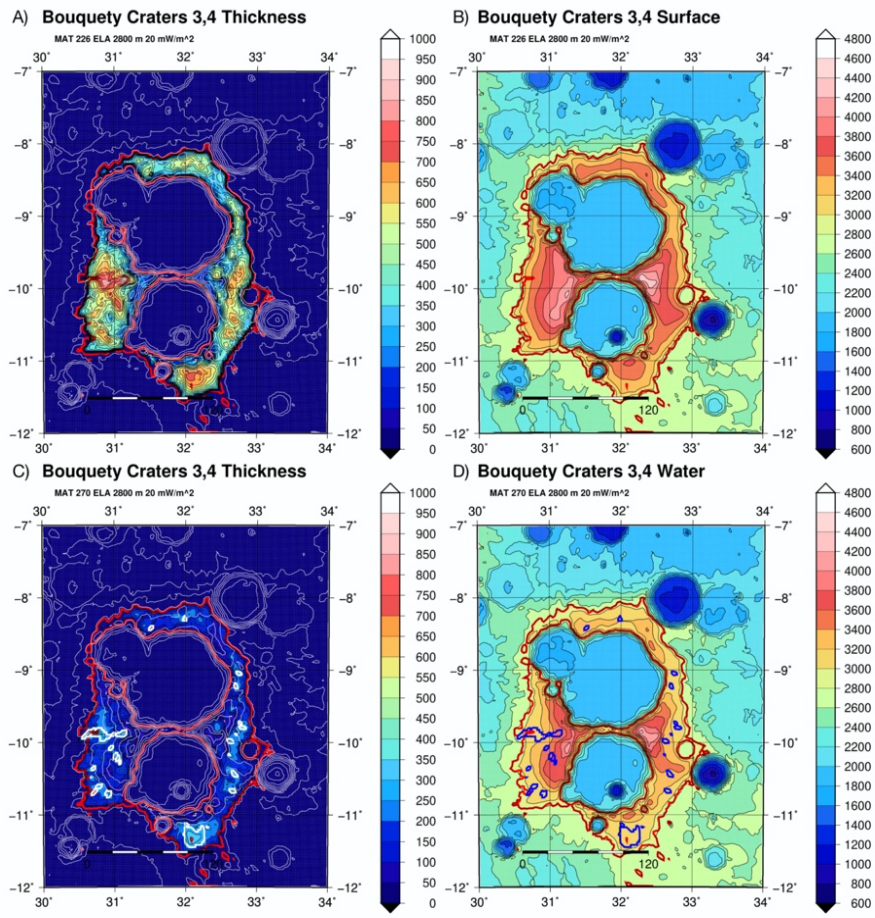

Figure 1: A), B) Thickness and surface for 226 K case, C), D) for 270 K case. Red outlines positive mass balance area. White in C) and blue in D) outline melted bed in 270 K case.

Discussion and Conclusions: We asked the following questions:

1) Is the configuration plausible? *Yes, for both 226 K and 270 K cases with significant difference in thickness, velocity, and amount of basal melting.*

2) What are the predictions and implications of the configuration of snow and ice, the ELA, and the position of melting? *The estimated ELA is too low to produce an ice cap consistent with Bouquety's [8] proposed outline. An ELA of 2800 m reproduces their outline well. Basal water in the 270 K case appears generally at the heads of the mapped VNs. Due to the lowering of the surface in the areas of fast flow, these would also concentrate surface melt runoff.*

3) Is the 270 K case the ambient climate or could it be a temporary/transitional climate***?*** *Given the short amount of time necessary to equilibrate, this could easily be a temporary/transitional climate.*

4) Is the interpretation most consistent with a 'warm/wet-warm/arid' or a 'Late Noachian Icy Highlands' ambient climate model? *Given that the LNIH climate, the 226 K case, produces no basal melting and liquid water in necessary for the transition from U-shaped to V-shaped valleys, the modeling favors 'warm/wet-warm/arid.'*

5) Does the modeling approach provide any insights into the validity or further applicability of the **[7,8]** interpretation*? On the basis of previous work on the configuration of a Late Noachian Ice Sheet [4], we interpret the ambient LN climate to be characterized by 'cold and icy highlands' conditions, and the climates represented by higher elevation and lower volume ice accumulations [7-8] to be related to a transitional warmer stage at the end of the Noacian. Thus, these areas and features [7-8] may provide a record of the transition to the Amazonian climate regime [15].*

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