VALLEY NETWORK FORMATION: PREDICTIONS FOR FLUVIAL PROCESSES IN A LATE NOACHIAN ICY HIGHLAND CLIMATE REGIME. J. W. Head and J. P. Cassanelli, Department of Geological Sciences, Brown University, Providence RI 02912 USA, (james_head@brown.edu).

I. Introduction: Improved 3D global simulations of the early martian climate by Forget *et al*. [1] and Wordsworth *et al*. [2] indicate that water ice is transported to the highlands from low-lying regions and preferentially trapped. As a consequence, an extended water ice cap forms on the southern pole (Fig. 1) and in the highlands, leading to a globally sub-zero Late Noachian 'icy highlands' (LNIH) climate scenario. With mean annual temperature (MAT) consistently well below 0°C [2], LNIH Mars is characterized by a global permafrost layer that forms a shallow perched aquifer (see summary in [3]) composed of a dry active layer whose thickness is defined by vapor diffusive equilibrium with the atmosphere (Fig. 1-1). Permafrost thickness is determined by local and regional geothermal heat flux and mean surface temperatures, is thinner than today and varies with altitude and latitude, likely averaging several km thick. To a first order, mean surface ice thickness will be determined by total water inventory and the percentage of the inventory available at and near the surface, neither value being well constrained for the Late Noachian. We assume that available surface ice was *supply limited* and about twice the current polar/near-surface ice inventory (~60 m GEL). In the equilibrium LNIH climate, orbital parameter variations cause regional redistribution of ice, with limited melting only under extreme circumstances [2]. *Punctuated non-equilibrium* top-down heating [3] could raise LNIH surface temperatures and cause melting. In order to test the LNIH model, we have 1) developed Late Noachian ice flow models [4], 2) assessed the post-depositional evolution of the accumulating snow as it converts to firn and ice [5], 3) outlined geological predictions for LNIH *equilibrium* environments and *equilibrium/non-equilibrium* melting scenarios [3], and 4) assessed insights into the icy highlands provided by the Antarctic Dry Valley hydrological system and cycle [3,6]. As a further test of the LNIH model, here we explore how *non-equilibrium* atmospheric heating and ice melting scenarios might be manifested in fluvial runoff, compared to the nature of valley networks (VN).

II. Predictions for Formation of Fluvial Channels: We assume that the meltwater source region is cold-based glacial ice, modeled under the conditions outlined for LNIH firn/ice development [5] and ice accumulation [4]. We assume that top-down heating of ice operates for a period of time (~10^1-10^3 yrs) sufficient to provide extensive meltwater, but insufficient for the melting isotherm to penetrate through the Late Noachian global permafrost layer. 1) **Melting and drainage of glacial snowpack**: Top-down melting of accumulated snow and ice will result in the initial rapid melting of the uppermost snow and firn [5] and its local drainage on top of the ice to low areas within the ice deposit or to the margins of the ice. In cold-based glaciers, top-down melting typically results in rapidly channelized meltwater that drains to the side and front of the glacier along surface cracks and crevasses [3]. 2) **Formation of fluvial drainage networks**: **a)** ***Initiation***: In contrast to widespread overland flow linked to pluvial activity, formation of fluvial drainage networks in LNIH environments would begin with the pattern of drainage off of the ice deposits. Typically these form streams that begin at the point where meltwater flows off the glacier, sometimes in waterfalls, and results in individual and parallel streams leading downslope, with low order and well developed relatively stationary individual channels. In the case of MDV seasonal melting [6], meltwater reoccupies the same fluvial channel, causing further incision and entrenchment. **b)** ***Fluvial channel substrate*:** Key to the evolution of fluvial channels is the nature and configuration of the substrate. In the LNIH, as in the McMurdo Dry Valleys [3,6], the initial substrate configuration (Fig. 1-1) is ice-cemented soil with an overlying dry active layer, producing a perched aquifer on top of the permafrost aquiclude. At the edge of the ice (Fig. 1-2), meltwater in the fluvial channel will soak into the dry active layer; infiltration will initially exceed runoff due to the ultra-dry nature of upper layer, a wetted hyporheic zone will surround the channel and as the soil becomes saturated, v-shaped valley incision will ensue. **c)** ***Fluvial channel evolution*:** Continuation of meltwater drainage (Fig. 1-3) causes vertical incision and erosion down to the top of the ice-cemented soil (the ice table, IT). At this point, erosion is favored laterally along the top of the ice table and the v-shaped channel transitions to a u-shaped channel. If flow is sustained, rather than ephemeral, heating at the bottom of the meltwater (Fig. 1-4) will cause thermal erosion of the ice-cemented soil, slow deepening, and continued widening of the u-shaped channel. **d)** ***Ice table/fluvial channel evolution*:** If top-down heating is sustained, the melting isotherm will penetrate deeper into the substrate (Fig. 1-5), and a new layer of water-saturated soil will develop, causing solifluction at the margins of the channels and collapse of water-rich sediment into the evolving and widening u-shaped channel. The descent of the ice table permits both widening and deepening of the fluvial channel; the rate of widening is likely to exceed the rate of deepening. If fluvial activity is sustained during the warming period, thermal erosion of the central channel will proceed more rapidly than the descent of the ice table (Fig. 1-5). **e)** ***Cessation of warming phase and return to LNIH equilibrium conditions*:** When top-down warming and melting subside and conditions return to the equilibrium LNIH state, the fluvial channel also undergoes significant changes (Fig. 1-6). First, the freezing isotherm re-establishes the ice table located outside the channel banks to the shallower pre-warming level. In the interior of the channel, near-surface, water-saturated fluvial sediments will freeze and then dehydrate as the new channel topography comes to vapor-diffusive equilibrium with the atmosphere (compare Fig. 1-1, 1-6). At the end of the warming phase, meltwater delivered to lower elevations by fluvial activity will freeze and be transported back to the highlands to renew the source region. A further important part of this new LNIH equilibrium configuration is that it pre-processes the substrate for the next phase of top-down heating and meltwater release. **f)** ***Repetitive heating and melting phases*****:** At the onset of the next phase of meltwater release (Fig. 1-6), meltwater is most likely to utilize the preexisting fluvial channel, and the floor of this channel will be occupied by unconsolidated and easily erodible fluvial sediments from the previous warming period. Erosion of the dry sediments down to the top of the ice table and to the edge of the channel will be dominant, favoring further vertical and horizontal incision of the channel as the meltwater channel fluvial processes repeat (Fig. 2-1 to 2-5). **g)** ***Predicted warming phase hydrographs*****:** Analysis of top-down melting of reconstructed LNIH ice profiles [5] suggests that the upper meters of snow and firn will melt relatively rapidly, followed by slower rates of melting of underlying ice. Thus, typical warming period hydrographs (discharge versus time) would be characterized by initial peak flow, followed by lower discharge for sustained flow, and ending with declining flow as the melting phase returned to equilibrium conditions.

III. **<u>Summary of Predictions for LNIH Valley Network Formation from Punctuated Melting</u>:** We formulate the following predictions for the nature of valley networks on the basis of the LNIH punctuated melting model. These LNIH predictions can be compared to the distribution, morphology and morphometry of valley networks [e.g., 7-9] to test further the LNIH model. **1)** ***Water sources*****:** LNIH snow and ice deposits provide an areally extensive and massive reservoir of potential meltwater for VN formation. **2)** ***Water release*****:** Nominal heating and top-down melting of snow and firn can rapidly release large volumes of meltwater. **3)** ***Top-down meltwater channelization*****:** Resulting flow off the ice is initially channelized at the ice margin and interacts with a dry active layer to start channel incision. **4)** ***Importance of fluvial icy substrate*****:** The fluvial substrate is a shallow perched aquifer superposed on an aquiclude defined by the ice table. Fluvial activity results in a predicted set of stages in channel evolution (Fig. 1) both during and between melting phases. **5)** ***Perched aquifer*****:** The presence of the shallow ice table aquiclude precludes deep meltwater infiltration and optimizes erosional capability. **6)** ***Return to equilibrium conditions: Water recycling*****:** At the end of the warming phase, meltwater that has drained to lower elevations will freeze and return to the highlands, replenishing the ice reservoir for the next warming phase. **7)** ***Reuse of existing fluvial channels*****:** Fluvial channels are destined to be reused multiple times and are likely to produce low stream order, entrenched fluvial systems. **8)** ***Global surface water inventory*****:** The robust recycling of meltwater back to ice source regions in the LNIH climate scenario places minimum requirements on the total Late Noachian surface water inventory.

References: 1. F. Forget *et al*., *Icarus,* 222, 81, 2013; 2. R. Wordsworth *et al*., *Icarus,* 222, 1, 2013; 3. J. Head *et al., LPSC 45*, 2014; J. Head, 5th Int. Wkshp. Mars Atmos., Oxford, UK, 2014; 4. J. Fastook, J. Head, *LPSC 45*, #1115, 2014; 5. J. Cassanelli, J. Head, LPSC 45, #1265, 2014; 6. J. Head, D. Marchant, in review, *Antarctic Science*, 2014. 7. R. Williams, R. Phillips, *JGR* 106, 23,737, 2001. 8. B. Hynek *et al., JGR* 115, E09008, 2010. 9. M. Hoke *et al., EPSL* 312, 1, 2011.

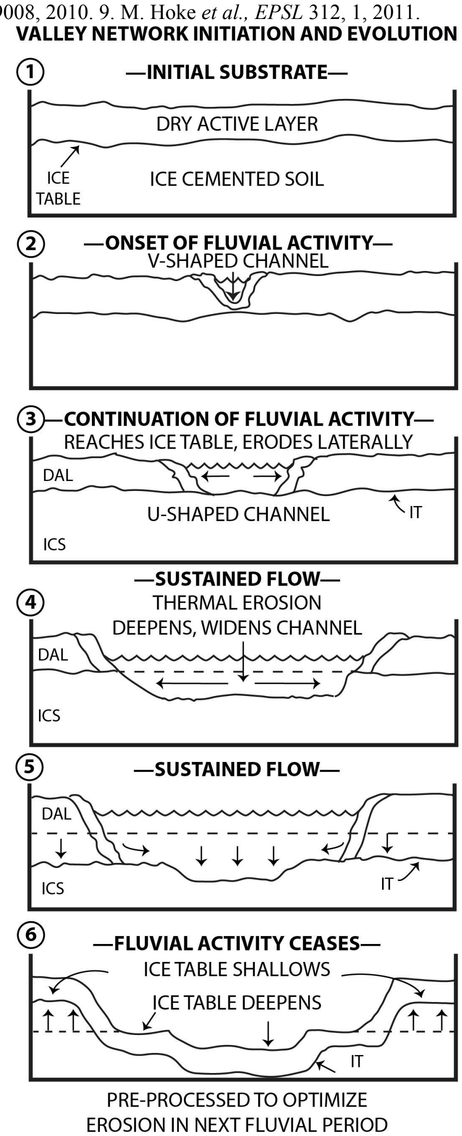

Fig. 1. Valley network substrate profile and channel evolution during punctuated top-down melting (DAL = dry active layer; IT = ice table; ICS = ice-cemented soil; hyporheic zone [3,6] indicated at channel edge.