ASSESSING THE FORMATION OF VALLEY NETWORKS ON A COLD EARLY MARS: PREDICTIONS FOR EROSION RATES AND CHANNEL MORPHOLOGY.
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Introduction: The ancient Noachian highlands of Mars host an extensive population of valley networks [*e.g.* 1]. While the origin of the valley networks by fluvial activity is almost universally accepted, whether the valley networks formed predominantly by rainfall in a warm and wet climate [*e.g.* 2,3], or by transient heating and snowmelt [*e.g.* 4] in an ambient cold and icy climate [5-7], remains disputed. Climate modeling studies [5-7] suggest that early Mars was characterized by a cold and icy climate exhibiting adiabatic cooling and an icy highlands, with mean annual surface temperatures almost 50 °C below the melting point of water. Under these conditions, rainfall-derived valley network formation is generally inconsistent.

If indeed the early climate of Mars was cold and icy as the models indicate, how might the nature of fluvial processes and the formation of valley networks have been influenced? Head and Cassanelli [8] proposed a conceptual model for channel incision and evolution under cold and icy conditions with a substrate characterized by the presence of an ice-free dry active layer and subjacent ice-cemented regolith, similar to that found in the Antarctic McMurdo Dry Valleys [9] (Fig. 1). In this scenario, the structure of the cold and icy substrate is predicted [8] to have an effect on erosional efficiency during channel incision, leading to preferential lateral erosion when the channel reaches the more coherent ice-cemented material (Fig. 1). Here we explore this conceptual framework through a quantitative assessment of the influence of cold and icy climate conditions, and the associated substrate structure, on the formation of valley networks. We outline predictions for: 1) the nature and structure of the substrate, 2) mechanical erosion and incision rates, 3) thermal erosion rates of the ice-cemented substrate, and 4) resulting geomorphic channel characteristics.

Substrate Nature: The primary factor predicted to affect valley network channel evolution under cold and icy conditions is the presence of an erosionally resistant ice-cemented regolith within the substrate [8]. The depth at which the substrate becomes ice-cemented (the ice-table) is governed by the diffusive equilibrium of water vapor with the atmosphere. We estimate equilibrium ice-table depths (following Mellon et al. [10]) under typical predicted Late Noachian climate conditions (1 bar CO_2 atmosphere and 45^o obliquity; [5-7]) using temperature and atmospheric water abundance data from recent global circulation model studies [11]. Results of this analysis predict that the valley networks occur in areas with equilibrium ice-table depths from ~50-100 m (varying with altitude and latitude), averaging ~80 m. This suggests that the infiltration capacity of the martian regolith would not be reduced by a shallow impermeable ice-table, thereby requiring a minimum threshold of surface water input to generate runoff.

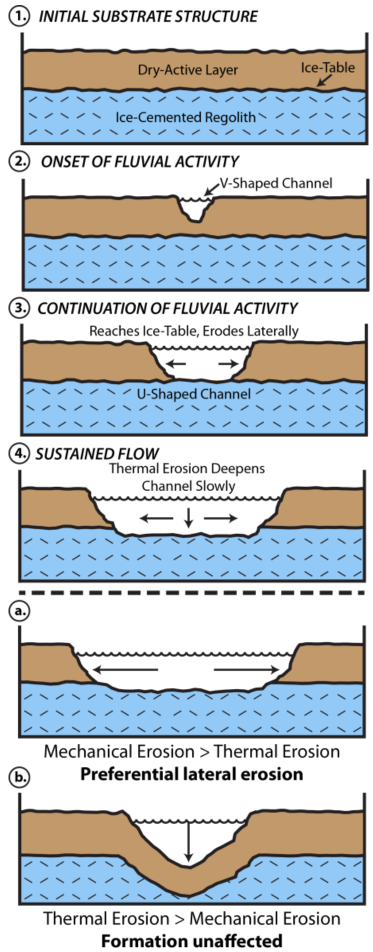

Figure 1. Conceptual model for channel evolution and valley network formation under cold and icy conditions [8]. The fluvial substrate is comprised of an ice-free dry active layer and ice-cemented regolith, with the interface between them being the ice-table [9].

Mechanical Erosion: The rate of channel growth in the ice-free substrate is governed by mechanical erosion produced by fluvial flow. To estimate the mechanical fluvial incision rates, we implement a simple stream power based estimate [12] (following Hurwitz et al. [13]), with the vertical erosion rate given by:

$$\frac{\partial z}{\partial t} = K\rho g Q sin(\alpha) \quad (1)$$

where K (Pa^{-1}) is a substrate erodibility factor expressing the efficiency of the incision process, and the remaining terms define the stream power [12,13]. Estimates of the mechanical erosion rate are sensitive to the value of the erodibility factor K [13], which is a poorly constrained parameter aggregating the effects of many factors [12] (*e.g.* substrate strength, sediment supply, grain size, and others). We adopt tentative erodibility factor values of 10^{-7} (for the ice-free substrate) and 10^{-8} (for the ice-cemented substrate) based on approximate values utilized by Hurwitz et al. [13]. The remaining parameters, related to the stream power, are calculated using estimated valley network flow data from Hoke et al. [14]. We find mechanical incision rates of ~$5x10^{-6}$ m/s in the ice-free substrate and ~$5x10^{-7}$ m/s in the ice-cemented substrate.

Thermal Erosion: Once the incising channel has reached the ice-table, vertical mechanical erosion will become more difficult as a result of the increased strength of the substrate. However, at this point, the ice-cemented substrate is subjected to both mechanical and thermal erosion. If thermal erosion rates are lower than the mechanical erosion rates, vertical erosion may be less efficient than lateral erosion, causing preferential channel widening (Fig. 1a). In contrast, if thermal erosion rates are higher than the mechanical erosion rates, the ice-cemented regolith will have little influence on channel incision and evolution (Figure 1b).

The rate of thermal erosion is governed by the flux of heat transferred into the substrate by the overlying fluid. In a turbulent flow regime (representative of the case considered here), this heat flux is given by [15]:

$$q = h(T_w - T_m) \quad (2)$$

where h is a heat transfer coefficient dependent upon the Nusselt number, which is calculated with an empirical relation [15]. Thermal erosion rates are assessed through the implementation of a simple 1-D finite difference heat conduction model. A constant heat flux, equal to that given by equation (2) is applied at one end of the model with an insulating boundary condition at the other, and any thawed material is assumed to be instantaneously removed from the system (therefore producing maximum thermal erosion rates).

We find that after the flow initially reaches the ice-table, melting is delayed for ~0.02 yr (~7 days) as the pore-ice is warmed to the melting point. After melting begins, thermal erosion proceeds at an average rate of ~$2x10^{-5}$ m/s, with a total long-term average (including the transient warming period) of ~$9x10^{-6}$ m/s.

Geomorphic Analysis: The conceptual model (Fig. 1) predicts that valley networks which interact with an ice-cemented substrate should exhibit increased width-to-depth ratios. To further evaluate this prediction, and our quantitative modeling results, we utilize morphometric data [16] of the valley networks to correlate measured width-to-depth ratios to predicted ice-table depths. The data show a weak tendency toward increased width-to-depth at shallower ice-table depths as the conceptual model predicts. However, we find no systematic correlation over the full range of parameters, suggesting additional factors are involved.

Conclusions: 1) Ice-Table Depths: In the valley network regions these are on the order of ~50-100 m, decreasing with altitude, and averaging ~80 m. This indicates that meltwater could infiltrate (and freeze) and mechanically erode the substrate for an extended period before reaching the ice-table. Any warm periods would have to be of extended duration (~2 kyr) in order for the surface temperatures to penetrate ~80 m to the ice-table to cause extensive melting of ground ice and induce solifluction/gelifluction activity. 2) Thermal Erosion: Predicted thermal erosion rates are comparable to the rates of mechanical incision in the ice-free substrate, and are greater than the rate of mechanical incision in the ice-cemented substrate, due to efficient heat transfer from the channel water to the substrate. 3) Role of Water Temperature: At the low meltwater temperatures consistent with a cold and icy early Mars environment [5-7], mechanical erosion rates can exceed thermal erosion rates, leading to channels undergoing preferential lateral expansion at the ice-table (Fig. 1), resulting in increased width-to-depth ratios. Over a wider range of conditions, we find that thermal erosion rates can exceed the mechanical rates, suggesting the permafrost ice-table may have been involved in preferential deepening of valley networks. 4) Morphologic/Morphometric Analysis: Regional analysis reveals a weak tendency toward increased width-to-depth ratios at shallower ice-table depths, consistent with the conceptual model predictions (Fig. 1). However, there is no significant correlation between valley network width-to-depth ratios and estimated ice-table depth, suggesting that additional factors are involved.

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