DID MARTIAN VALLEY NETWORKS FORM UNDER ANCIENT ICE SHEETS?

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Introduction: Hundreds of valley networks incise the surface of the ancient southern hemispheric highlands of Mars [1]. The presence of these systems, the fossil remnants of large valleys incised by liquid water, has important implications for the climate conditions and habitability of early Mars 4.1–3.1 Byr ago [1,2], and yet the details of their emplacement remain disputed.

The close resemblance of valley network planform morphology to that of fluvial valleys on Earth [3,4] led to the suggestion that rainfall and surface runoff were responsible for the origin of these enigmatic features, constraining the climate of early Mars to a much warmer environment allowing for surface water stability [3]. However, state-of-the-art 3D climate models [5], incorporating the effects of topography and the reduced incoming radiation from a younger and fainter Sun, predict the build-up of kilometer thick ice sheets on the southern highlands, implying a correlation between snow and ice accumulation and valley networks [6,7]. Protracted rainfall and surface runoff would become unattainable under a wide range of model predictions for early Mars, in contradiction with morphological evidence [5,6].

In this study, we provide the first classification scheme for valley network formation based on linking the morphological variability existing in valley network planform and longitudinal profile to the physical characteristics derived from different mechanisms of valley incision, including steady fluvial, glacial, sapping, and subglacial erosion [8].

Our findings, supported by both quantitative observations of valley network characteristics and qualitative comparisons to subglacial channels in the Canadian Arctic Archipelago (Fig.1), support a new hypothesis for valley network formation: erosion by subglacial channelized meltwater, the drainage pathways of a Late Noachian Icy Highlands ice sheet [7]. This hypothesis best explains several puzzling valley network morphological characteristics [8,9], and reconciles morphological observations and climate model predictions for early Mars.

Methodology: We used a Principal Component Analysis (PCA) constructed on the basis of 6 landscape metrics that capture distinctive morphometrical properties of 66 valley networks, understood with physical models of fluvial, glacial, sapping, and subglacial erosion, to establish the first rigorous global classification scheme for Mars' valley networks [8].

Fig. 1: Example of a dendritic subglacial channel network located at the North West of Devon Island (image center 75.83N, 90.55W). Image credit: Landsat/ Copernicus.

In detail, we examined 5 aspects of valley network planform morphology, the length to width aspect ratio along the longest tributary, the statistical angle of tributary junction, the highest stream order (Horton number) of the network, the width of order 1 tributaries (minimum width), and network fractal dimension. We also analyzed longitudinal profile curves along the longest tributary to quantify the interaction between landscape and erosional process: sections of valley longitudinal profile displaying a positive topographic gradient that is unexplained after considering known surface tectonics, impact craters and their ejecta, and infill from tributaries, require pressure gradients driving water flow, consistently with subglacial but not with surface runoff [10, 11]. Profile concavity characteristics, additionally, are a measure of whether a fluvial valley reached steady-state and indicate whether the drainage was consistent with precipitation or not.

Results: We use a PCA (Fig. 2), understood with model predictions, to classify the set of 66 valley networks according to their originating process [8]. Figure 2 shows this classification based on their morphological characteristics (metrics, upper right) and their consistency with models of erosion (colored areas).

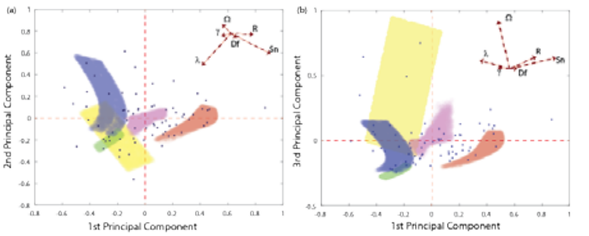

Fig. 2: 1st and 2nd Principal Components (PC) (left) and 1st and 3rd PC (right) showing the classification of the 66 valley networks (black dots). Model predictions show fluvial valleys in red, subglacial in yellow, glacial in blue, sapping in green, and statistically undifferentiated in magenta [8].

We also show how the largest portion of valley networks are undifferentiated (magenta) and likely did not reach landscape steady state. This observation is consistent with the difference to model results from steady-state solutions of common landscape evolution equations, adapted to the Martian parameter space [8].

Qualitative observations based on morphological comparison between subglacial channels on Devon Island (Canadian Arctic Archipelago, see Fig.1) and valley networks on Mars further support the quantitative analysis [8,11]. Although the scale of the Martian valley networks is larger, morphological characteristics such as the undulating profiles, invariant cross-sectional scales as the system evolves downstream, large first order tributaries, absence of inner channels, discontinuous segments, and a low number of delta fans are common features in most of the terrestrial subglacial channelized drainages [10].

In addition, evidence of subglacial drainage has been identified in a number of locations on Mars' surface, and across Mars' history. Observations of undulating longitudinal profiles in Amazonian-aged fresh valley networks motivate their interpretation as remnants of subglacial channels [12]. Extensive systems of eskers are also inferred within the ancient Dorsa Argentea formation [13]. Furthermore, recent radar evidence for a subglacial liquid body of water under the current southern polar cap [14] indicates the resilience of subglacial liquid meltwater under large bodies of ice, as well as and its ability to flow.

Discussion: Figure 3 shows a map projection of the valley networks we analyzed, coded according to the results of our classification in Figure 2. In addition, we represent the climate model predictions for the ice accumulation and equilibrium lines for a Late Noachian Icy Highlands ice sheet at 15X the current water inventory of Mars [7].

The distribution of fluvial valley networks closely follows the topographic gradient that limits Arabia Terra. Most of the fluvial valleys are incised in mid-Noachian terrains and appear below the ice equilibrium lines corresponding to the late Noachian period.

Subglacial valley networks are widespread, incising mostly mid- to late-Noachian terrains and appearing both above and below the ice equilibrium line predicted for the late Noachian. In some locations (see arrows) fluvial and subglacial drainage appear in close spatial proximity, suggesting either climate variability through time of the presence of the ice margin at that location. Detailed timing of valley network formation is necessary to draw further interpretations.

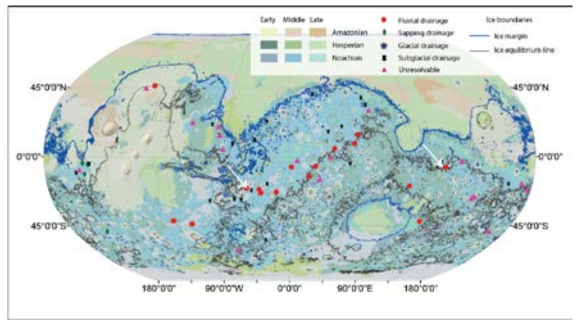

Fig. 3 Classification results in fig. 2 overlapping a geological map of Mars (terrain age is color coded). Fluvial valleys are coded with red circles, subglacial valleys are coded with black pushpins, glaciers are blue asterisks and sapping valleys green diamonds. Magenta points are unresolvable. Ice accumulation is marked with a light blue line, and ice equilibrium is a dark blue line.

Conclusions: Our main conclusion is that geomorphologic and geological data require that early Mars was a frozen world akin to present day Antarctica, with an active hydrological cycle beneath the ice, sporadic fluvial erosion, and mostly short-lived valleys that did not reach landscape steady-state (magenta valleys in Fig. 2). Our work presents the first robust observational support for state-of-the-art climate models and provides a new framework for identifying astrobiologically interesting environments on Mars.

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