PLANETARY SCIENCE

Branching geometry of valley networks on Mars and Earth and its implications for early Martian climate

Hansjoerg J. Seybold[1]*, Edwin Kite[2], James W. Kirchner[1,3,4]

Mars' surface bears the imprint of valley networks formed billions of years ago. Whether these networks were formed by groundwater sapping, ice melt, or fluvial runoff has been debated for decades. These different scenarios have profoundly different implications for Mars' climatic history and thus for its habitability in the distant past. Recent studies on Earth revealed that valley networks in arid landscapes with more surface runoff branch at narrower angles, while in humid environments with more groundwater flow, branching angles are much wider. We find that valley networks on Mars generally tend to branch at narrow angles similar to those found in arid landscapes on Earth. This result supports the inference that Mars once had an active hydrologic cycle and that Mars' valley networks were formed primarily by overland flow erosion, with groundwater seepage playing only a minor role.

INTRODUCTION

Decades of satellite missions to Mars have shaped an evolving narrative of the history of water on the red planet. Early missions returned images showing ancient channel networks but no concrete evidence for flowing water (1–4). Mars' cold present-day climate, combined with Earth-analog fieldwork, led to the hypothesis that Mars' channel networks could have been carved by streams sourced from groundwater springs (5–8). However, it remains unclear how these processes could lead to branching networks of kilometer-wide valleys incised into bedrock (9, 10). Uncertainty concerning the valley incision process is closely coupled to the question of early Martian climate and habitability. Fluvial runoff erosion would require very different climatic conditions than those that we observe today on Mars. Frequent precipitation and an active hydrological cycle (10–14) are necessary to support a significant amount of overland flow, with temperatures at least episodically rising sufficiently to allow liquid water to exist (12–17), implying that a thicker CO_2 atmosphere is a necessary factor.

Recent observations from spacecraft (18, 19) and from Mars meteorites (20) have provided evidence for long-lived, potentially habitable lakes and seas approximately 3.7 Ga on Mars, when most valley networks were formed. However, a lack of geologic constraints has hampered quantitative reconstruction of Mars' paleoclimate. Correctly interpreting Mars' climatic history is important because Mars is the only planet known to have undergone a major transition in planetary habitability, from more habitable in the past to less habitable today. This transition may be recorded in Mars' geology and geomorphology, and planetary scientists have struggled for decades to identify surface characteristics that can be used to unravel Mars' climatic past. In particular, many of the tools developed to relate geomorphic form to process on Earth are inapplicable on Mars because they require grain-size measurements that are unavailable except at a handful of possibly unrepresentative landing sites. New worlds challenge us to develop new tools.

MATERIALS AND METHODS

Here, we explore how the geometry of Mars' channel networks can provide insight into how they were formed and thus help constrain Mars' climatic history. Recently, a study of channel networks across the United States has shown that their mean valley branching angles (as distinct from local junction angles; see the Supplementary Materials) are correlated with climatic aridity, independent of other factors such as stream order, drainage area, or slope (21). Valley networks tend to branch at narrower angles in arid climates, where flash floods and overland flow are more common, while humid landscapes with more groundwater recharge are characterized by wider branching angles (21). Figure 1 shows, for the first time, that this relationship between valley network geometry and climatic controls is observed not only across the United States but also in coarser-scale global maps (for details, see the Supplementary Materials).

The observed relationship between mean valley branching angles and climatic aridity implies that these features also reflect the relative importance of different channel-forming processes. Runoff variability, and thus the amount of geomorphically effective streamflow (22) per unit precipitation, is higher in more arid landscapes (23–26). Conversely, groundwater should be geomorphically less important in more arid landscapes, where aquifers are more decoupled from the surface (21, 27, 28). Where recharge rates are low, and aquifers are largely decoupled from the surface [low water table ratio (27)], mean valley branching angles are narrow (21). Thus, valley network branching angles should be helpful in estimating the relative importance of surface runoff and groundwater, particularly on extraterrestrial planets where direct field observations are difficult.

RESULTS AND DISCUSSION

Here, we illustrate this approach using two independent high-resolution global data sets of Martian valley networks (Fig. 2A). Hynek et al. (29) manually extracted Martian valley networks from infrared images with a pixel size of ~230 m, and Luo and Stepinski (30) used automated extraction techniques to define valley networks from gridded laser altimeter data with a spatial resolution of about 128 pixels per degree, corresponding to roughly 463 m at the equator. Two example networks from Hynek et al. (29) are shown in Fig. 2 (C and D). These networks show a narrowly "feathered" geometry, similar to networks formed by overland flows in arid regions on Earth.

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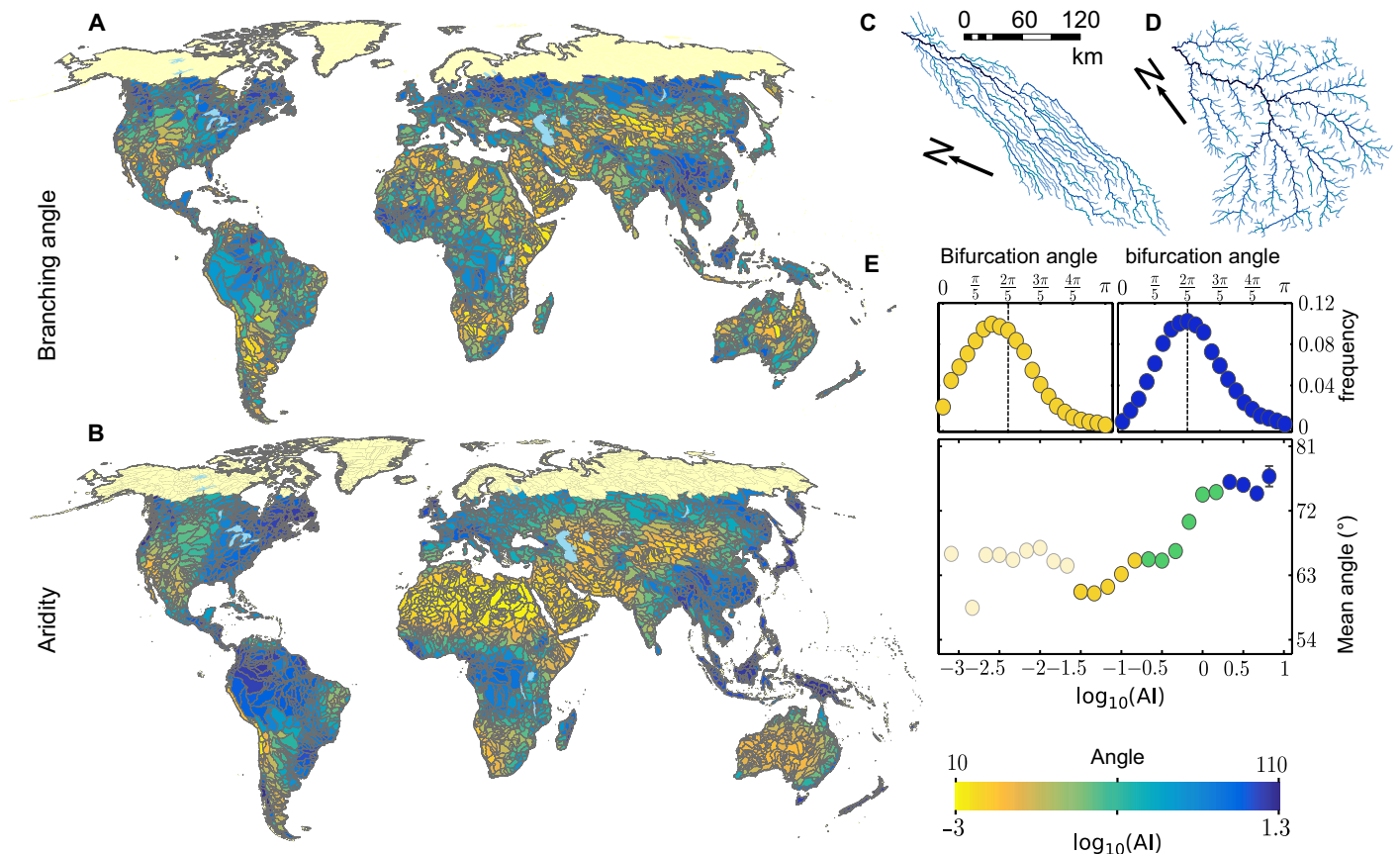*Corresponding author. Email: hseybold@ethz.ch

Fig. 1. Global distribution of mean branching angle and aridity index. Global distribution of mean river network branching angles (**A**) and aridity index (AI) (**B**) averaged over the level 4 basins defined by the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) data set. Narrow branching angles are more likely to occur in arid regions (low AI, yellow), while in humid regions, branching angles are usually wider (high AI, blue). Latitudes north of 50°N where no stream data are available are marked in cream. (**C** and **D**) Examples of stream networks from arid (C) and humid landscapes (D). The arid network is located in eastern Algeria, and the humid network lies in the Amazon rainforest at the border between French Guiana and Suriname. Mean branching angles for binned ranges of AI are shown in (E), together with the corresponding branching angle histograms for the arid (yellow) and humid (blue) tails, respectively. The points with $\log_{10}(AI) < -1.5$ are shaded because they constitute only a small fraction (<5%) of the whole data set spread over a wide range of aridity values; their inclusion or exclusion has no visually detectable effect on the global branching angle distribution.

The global surveys of network branching angles on Mars confirm the generality of this observation. Figure 2B shows the branching angle statistics for the Hynek *et al.* (*29*) and Luo and Stepinski (*30*) network data sets. Although the two sets of networks have been extracted independently using different techniques, their branching angle distributions differ only slightly, both peaking around 40° ± 5°, (modes calculated by kernel density smoothing). These narrow characteristic angles suggest that Mars' valley networks may follow the regional topographic slope more closely than typical networks on Earth (*31*), which are often embedded into a smoothly varying landscape of valleys and hilltops, especially in more humid regions.

The solid line in Fig. 2B compares the branching angles of the Martian networks with those of the streams of the Upper Colorado-Dirty Devil basin in the arid southwestern United States (HUC 1407, Fig. 2E), as mapped by the NHDPlusV2 data set (see the Supplementary Materials). This basin and its surroundings are thought to resemble a Martian landscape (*32*, *33*), and astronauts train there at the Mars Desert Research Station (MDRS) in anticipation of future Mars missions. Although the mapping resolutions of valley networks differ by almost a factor of 10 between Mars and the desert southwest United States, their branching statistics are strikingly similar.

The mode of the branching angle distribution of the Upper Colorado-Dirty Devil basin is approximately 41°, consistent with the global distribution on Mars. To check that this is not just a coincidence, we also analyzed the branching angles of two neighboring basins (fig. S2), which peak around 36° and 34°, respectively. Junction angles also vary with slope (*21*), but all of the networks shown in Fig. 2B have broadly similar slope distributions (fig. S3), suggesting that slope differences are unlikely to be masking aridity differences between the Mars networks and Earth analogs. The characteristic valley branching angles observed on Mars and in the desert southwest are significantly narrower than the characteristic branching angles observed in humid regions with higher groundwater recharge.

These observations support the interpretation that Mars' channel networks were mainly formed by surface runoff driven by episodic precipitation events in an arid climate. This hypothesis is also supported by observations from drainage basin morphology (*32*) and erosional models (*33*, *34*). A dry continental climate in the low- to mid-southern latitudes, where most of the valley networks reside, is consistent with the hypothesized ocean covering most of Mars' northern hemisphere (*35*–*38*). Such a hemispheric segregation would imply an increasingly arid continental climate toward the south
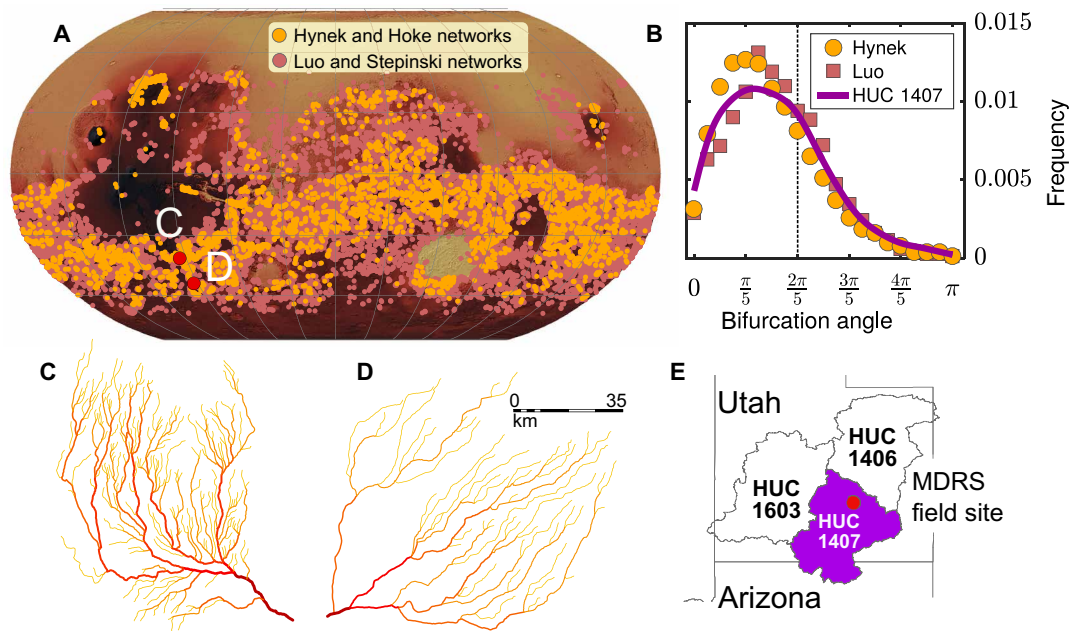
Fig. 2. Comparison of mean valley branching angles on Mars and arid landscapes on Earth. (**A**) Outlet locations of the valley networks mapped by Hynek *et al*. (*29*) (orange) and Luo and Stepinski (*30*) (rose color). Background shading indicates elevation. The corresponding branching angle distributions are shown in (**B**). The violet solid line represents the branching angle distribution in the Lower Green River, a basin in the arid southwestern United States. The modes of the three data sets are 36° for the Hynek and Hoke networks, 45° for the Luo and Stepinski networks, and 41° for the Upper Colorado-Dirty Devil basin (HUC 1407). These values are considerably smaller than the theoretical angle of 2π/5 = 72° (*45*) expected for groundwater-driven network growth (black dashed line). Two sample valley networks on Mars are shown in (**C**) and (**D**). Scale bar corresponds to both sites. (**E**) Map of the Upper Colorado-Dirty Devil basin (HUC 1407), where the MDRS (red circle) is located.

(*10, 39*), with limited channel formation and lower drainage densities further to the south (*10, 29, 40, 41*).

To rule out the possibility that narrowly branched drainage patterns also result from channelization in permafrost landscapes, we analyzed the high-resolution National Hydrography Dataset (NHD) drainage networks for the State of Alaska (see the Supplementary Materials). Figure 3 shows the branching angle statistics separated into regions with continuous, intermittent, and sporadic permafrost (violet, magenta, and green, respectively), where we pruned all first-order valleys to achieve a comparable resolution to the NHDPlusV2 data for the rest of the continental United States (see also fig. S4). All three groups of networks have branching angle distributions that peak close to 72°, significantly wider than the branching angle distributions observed on Mars.

CONCLUSIONS

Most valley networks on Mars are thought to have been formed in a rather short epoch during the Late Noachian and Early Hesperian (*42, 43*). Lake coverage and valley incision depth both suggest a climatic optimum (*11, 12, 42, 44*) during this epoch. While many smaller tributaries may have been erased over time, and channels on valley floors are only rarely preserved, the planform branching pattern is probably the least-altered geomorphic feature of these networks, in some cases even surviving channel inversion (*13*). The correlation of branching angles with climatic controls supports the recent shift from groundwater-dominated theories for Martian channel formation (*5–7*) to more recent precipitation-based theories (*10–12, 16, 40, 43*). Our analysis suggests that Mars' channel net-
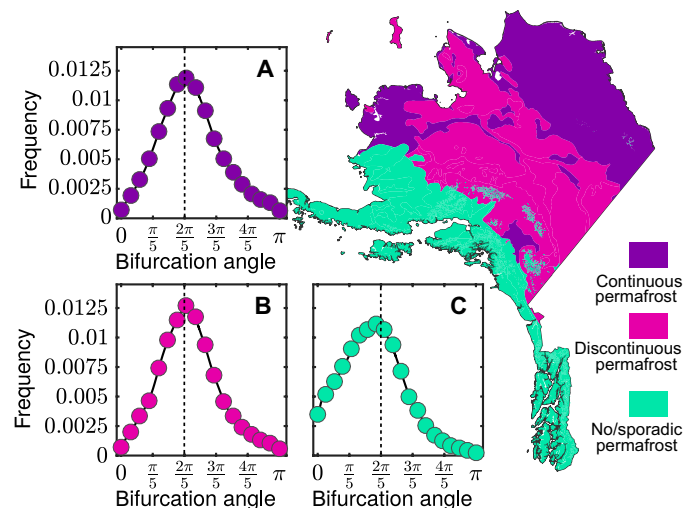

Fig. 3. River network branching angles in the State of Alaska. River network branching angles in the State of Alaska, separated into regions with continuous permafrost (violet; **A**), discontinuous permafrost (magenta; **B**), and absent or only sporadic permafrost (green; **C**). In all three cases, the bifurcation angle histograms peak at roughly 72° (dashed lines), similar to the branching angles observed in other humid landscapes. The black solid lines in (A) to (C) show the kernel-smoothing density estimates of the branching angle distributions.

works were formed in an arid continental climate with sporadic heavy rainfall events large enough to create significant surface runoff. Our results imply that the growth of Martian valley networks was dominated by near-surface flow and that groundwater sapping played a relatively minor role.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/6/eaar6692/DC1

Global aridity and branching angles

NHDPlusV2 data analysis

NHD data analysis for the State of Alaska

fig. S1. Measurement of the branching angle as defined in (*21*).

fig. S2. Branching angles for two basins in the arid southwest of the United States.

fig. S3. Histograms of valley slope for the two Mars data sets (Hynek and Hoke, orange circles; Luo and Stepinski, rose-colored squares) and the Upper Colorado-Dirty Devil basin (HUC 1407, violet solid line) as mapped by the NHDPlusV2 data set.

fig. S4. Branching statistics of the raw NHD streams of the State of Alaska (*50*) categorized in regions with continuous permafrost (violet), discontinuous permafrost (magenta), and no permafrost (green).

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