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Did Martian valley networks substantially modify the landscape?

Anna Grau Galofre^a, Rickbir Singh Bahia^b, A. Mark Jellinek^c, Kelin X. Whipple^a, Rose Gallo^d

^a*School of Earth and Space Exploration, Arizona State University*

^b*School of Earth, Atmospheric and Environmental Sciences, The University of Manchester*

^c*Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia*

^d*School of Earth and Sustainability, Northern Arizona University*

Abstract

Valley networks are ancient drainage systems incised on the southern hemisphere of Mars, and stand as evidence that liquid water once sculpted its surface. The duration of valley network activity and the sources of water are key questions in deciphering the timing of water stability on early Mars, but remain poorly constrained. In this study we address two questions: Did Martian valley networks evolve for sufficiently long to establish their own erosional basins, or do their profiles primarily reflect landscape pre-incision topography? And were these valleys precipitation-fed or spring-fed? Our analysis uses the theoretical framework built to describe the shape of steady-state river profiles on Earth to compare and analyze the concavity of 62 valley network longitudinal profiles on Mars. Using non-linear fits to valley profiles we evaluate the degree to which valley networks are consistent with fluvial steady-state. The fit enables the identification of valley network concavity index and area-discharge exponent, which we then interpret in terms of the theoretical framework to discuss valley network maturity and water source. Our results show that the majority of valley networks do not have concave or even smooth profiles, and did not substantially

*Corresponding author: Anna Grau Galofre (agraugal@asu.edu)

modify their surrounding landscape. We observe disparity in concavity indexes of valley networks belonging in the same integrated basins, indicating different stages of landscape evolution and lack of synchronous valley development. However, our results identify six valley networks consistent with fluvial steady-state and areally uniform precipitation.

Keywords: Mars, Valley networks, Maturity, Fluvial erosion, Profile analysis, Precipitation

1. Introduction

Thousands of valley networks are etched into the southern hemispheric highlands of Mars, standing as evidence that water sculpted the ancient surface of the planet. Martian valleys are dendritic tributary networks incised mostly into the heavily cratered ancient Noachian terrains (~ 3.8 Ga). A heated matter for debate is the requirements that the presence and morphology of these valley networks place on early Mars climate [1, 2], specifically whether liquid water was stable for long or short periods of time on the surface of Mars.

Although it is generally agreed that liquid water was involved in valley formation, controversy remains over the duration and intensity of the erosion episodes [3, 4, 1, 5, 6, 7, 8], as well as over the source of the water: rainfall [1, 6, 9, 8], snowfall and snowmelt [10, 2], groundwater seepage [11, 12, 4] (see however [13]), etc. Here we seek to answer two questions: Were valley networks active for long enough to significantly alter the landscape, and generate well-established drainage basins? Was precipitation-driven runoff required or could groundwater produce the observed landforms?

A way to evaluate the extent to which fluvial processes have modified the landscape is to interrogate the concavity index (slope-area exponent) of valley longitudinal profiles in terms of the theory describing river valleys in steady-state [e.g., 14, 15, 16, 17]. “Mature” river valleys reflect in the concavity of their

smooth profiles either a balance of tectonic uplift and erosion rates (bedrock rivers) or a local equilibrium between sediment transport capacity and sediment supply (alluvial rivers) [e.g., 14, 15, 17, 18]. The characterization of river concavity in the context of landscape equilibrium has been the focus of much attention for terrestrial rivers [e.g., 14, 15, 16, 17, 19, 18]. On Mars, several studies have extracted valley profile concavity from area-slope scaling laws, and compared it qualitatively to terrestrial standards [e.g., 20, 5, 21, 22, 23]. The focus and novelty of this study is to apply the terrestrial theoretical framework to help interpret the concavity of a large number of Martian profiles, with focus on their maturity and the characteristics of the runoff source.

1.1. *Structure*

We compare the concavity of main stem profiles to steady-state solutions of fluvial landscape evolution equations [16, 19, 18]. Using a dataset of 62 valley network longitudinal profiles, we show how each profile compares to (or departs from) steady-state model predictions, and identify those valley networks that have substantially modified the landscape around them. We then compare our results with observations drawn from morphological metrics commonly invoked to assess the degree of valley maturity [24, 25, 8]. We discuss the distribution of valley networks with profiles consistent with fluvial landscape equilibrium, and for these systems, we characterize the water sources expected for the drainage basins [16, 7, 18]. We finish by considering the results obtained in the context of three large integrated basins: the Loire-Parana-Samara, the Naktong-Scamander-Mamers, and the Evros-Mosa drainage systems.

2. The concavity of steady-state fluvial profiles

Historically, the formation of the Martian valley networks has been attributed either to surface runoff [1, 7, 6, 9], or to groundwater sapping [11,

26, 4]. Fluvial erosion can occur in two regimes: bedrock rivers (the so-called detachment-limited regime [16, 7]) erode the bed via the sediments they carry through a combination of plucking and abrasion [17]; and alluvial rivers erode substrates that offer low resistance to detachment, erosion, and transport (the so-called transport-limited regime, [17, 18]).

On Earth, tectonic uplift and the resulting production of steep topography yield the high shear stress conditions necessary for the formation of bedrock rivers. Lacking orogenesis, craters dominate the regional slopes, whereas Tharsis and the dichotomy boundary set the long-wavelength Martian topography. Craters disrupt the landscape, produce highly erodible ejecta and hard crater floors, and have a long-term diffusive effect on the landscape [7]. Whereas stratigraphy shows that bedrock rivers existed on Mars [9], it is likely that the gentler slopes and more friable substrates characteristic of the intracrater plains led to the development of alluvial valley networks.

Erosion by sapping constitutes another hypothesis for valley network formation [11, 26, 4], although it is problematic in cohesive substrates [13, 27]. Sapping valleys develop when groundwater emerges at a spring, producing erosion at the site of seepage leading to the headwards development of a valley. The steady-state shape of sapping valley longitudinal profiles is governed by distinct physics at two length scales. Near the spring, the longitudinal profile decreases with the distance from the tip with an exponent of $2/3$ [28]. However, at the valley network basin length scales (100-1000 km) [5], erosion by surface runoff dominates the formation and shape of the drainage network [28]. A sapping signature should only be apparent in the first order tributaries [28].

Coherently, here we build upon a theoretical framework describing basin-scale valley network longitudinal profiles that includes both alluvial and bedrock rivers, but not sapping valleys.

74 *2.1. Modeling the effects of fluvial erosion*

75 Steady-state river longitudinal profiles are empirically described by Flint's
 76 law (equation 1), which relates slope $\partial z/\partial x$ and upstream drainage area or
 77 length x (through Hack's length-area relationship $A = K_a x^h$ [29]). Previous
 78 work has demonstrated that valley networks also follow a slope-area scaling
 79 [23, 30]:

$$80 \quad \frac{\partial z}{\partial x} = K_s (K_a x^h)^{-\theta}, \quad (1)$$

81 where K_s is the steepness index, K_a is Hack's law parameter, h is Hack's expo-
 82 nent, and θ is the concavity index. Direct integration of this equation assuming
 83 that all variables are spatially homogeneous yields the empirical shape of a
 84 steady-state fluvial profile, where L is the basin length:

$$85 \quad z(x) = K_s K_a^{-\theta} (1 - h\theta)^{-1} [L^{1-h\theta} - x^{1-h\theta}]. \quad (2)$$

86 The form of equation 2 describes both alluvial and bedrock equilibrium river
 87 profiles [16, 17, 18] independently of gravity, making it applicable to any solar
 88 system body. Whereas the concavity index θ of a steady-state river varies within
 89 a narrow, distinctive range [14, 16, 17, 18], the interpretation of the coefficient
 90 K_s differs depending on the erosive regime. The existence of a general form de-
 91 scribing transport and detachment-limited river profiles in equilibrium 2 allows
 92 for the identification of valley networks consistent with fluvial steady-state with-
 93 out making assumptions regarding the mechanics of landscape equilibrium, as
 94 developed below. As a result, our methods and conclusions are easily extendable
 95 to previous morphometrical analysis of profile concavity [20, 22, 23].

96 *2.1.1. Steady-state fluvial longitudinal profiles*

97 Under the detachment-limited regime, the longitudinal profile form of a
 98 bedrock river in steady-state is given by the solution to the stream-power law,

99 which in non-dimensional form is written [e.g., 14, 16, 17, 7]:

$$100 \quad z_*(x_*) = z_*(1) - N_e^{1/n} U_*^{1/n} (1 - hm/n)^{-1} \left(1 - x_*^{1-hm/n}\right), \quad (3)$$

101 where z_* and x_* are non-dimensional elevation and length, U_* is the normalized
 102 uplift rate, n is the slope exponent, m/n is the bedrock concavity index, and the
 103 non-dimensional uplift-erosion number N_e contains the dimensional information
 104 [16]. This equation can be rewritten to recover the form of equation 2 [16]:

$$105 \quad z_* = K_d - K_d x_*^{1-h\theta} \quad (4)$$

106 The two coefficients in equation 4 can be identified with those in equation 3 as
 107 a function of the steepness index $K_d = K_s K_a^{-\theta} (1 - h\theta)^{-1} L^{1-h\theta}$ and concavity
 108 index $m/n = \theta$.

109 Considering now transport-limited rivers and assuming negligibly small up-
 110 lift rates ($U \rightarrow 0$), the steady-state profile of an alluvial river follows (modified
 111 from equation 40 [18]):

$$112 \quad z = \left(\frac{x_o^{1+6ch(b-1)/7} - x_o^{1+6ch(b-1)/7}}{x_1^{1+6ch(b-1)/7} - x_o^{1+6ch(b-1)/7}} \right) + 1, \quad (5)$$

113 where x_o and x_1 are the positions of the origin and downstream boundary, and
 114 b and c are the discharge-width and the discharge-area exponents. Equation 5
 115 can be non-dimensionalized and written to recover equations 2 and 4:

$$116 \quad z_* = K_t - K_t x_*^{1-6/7h\theta_t}. \quad (6)$$

117 With coefficient $K_t = K_s K_a^{-\theta} (1 - h\theta)^{-1} L^{1-h\theta}$. The slight difference between
 118 the alluvial concavity index $\theta_t = 7/6\theta$ and the bedrock one $m/n = \theta$ results from
 119 different choices describing water turbulent stresses in the literature [16, 18] and

120 does not affect the form or interpretation of the equation. Note also that the
 121 coefficients K_t in 6 and K_d in 4 are related in the same way to the steepness
 122 index K_s but each have different definitions (5 and 3).

123 2.1.2. Basin-scale valley network degradation

124 Martian valley networks have been subjected to degradation processes for
 125 over 3.5 Ga. On Mars, wind, mass-wasting, cratering, and dust blanketing po-
 126 tentially modified the initial shape of valley networks and their profiles. Whereas
 127 it is possible for diffusive processes to erase small tributaries and higher fre-
 128 quency topography, it is unlikely that they had any significant effect on basin-
 129 scale profile concavity. A scaling argument (supplement) shows that diffusion
 130 modifies the topography at a valley width scale by a half of local valley network
 131 depth (order ~ 100 m). The longitudinal profile shape, however, is set by total
 132 basin scale relief and length, which is at least an order of magnitude larger.
 133 The different length scales of action, exemplified by the ratio of width versus
 134 length, show that diffusion has not substantially modified longitudinal profile
 135 concavities.

136 2.1.3. Parameters and exponents: building intuition

137 We present a theoretical framework [16, 7, 18] to inform the interpretation
 138 of the concavity index θ . The following arguments are drawn from analyzing
 139 bedrock rivers but equivalent relationships have been developed for alluvial sys-
 140 tems [18]. Derivation of erosion models part from the reasonable assumption
 141 that erosion rates have a power dependence on shear stress:

$$142 \quad E = K_b \tau_b^a, \quad (7)$$

143 and combines the following semi-empirical relationships from momentum con-
 144 servation, hydraulic geometry, basin hydrology, and basin geometry, in turn, to

145 establish a closure for the shear stress τ_b :

$$\begin{aligned}
 \tau_b &= \rho g D S = 1/2 C_f v^2 \\
 W &= k_w Q^b \\
 Q &= K_q A^c \\
 A &= K_h L^h,
 \end{aligned}
 \tag{8}$$

147 where D is flow depth, and v is flow velocity. Combining equation 7 with
 148 equations 8:

$$E = K A^{2ac(1-b)/3} S^{2a/3}.
 \tag{9}$$

150 Comparing this equation with the closures in equations 7 and 8, the slope ex-
 151 ponent n , concavity index m/n , and Hack's reciprocal exponent h depend on
 152 a, b, c through:

$$\begin{aligned}
 n &= 2a/3 \\
 m &= 2ac(1-b)/3 \\
 m/n &= \theta = c(1-b),
 \end{aligned}
 \tag{10}$$

154 with $h \approx 1.35$ from empirical fits to Martian valley networks [29, 5, 21, 23].
 155 The exponent a in 7 sets the intensity of the erosion rate as a function of shear
 156 stress [16], and takes values between 1 and 5/2 in terrestrial bedrock rivers [e.g.,
 157 16, 19]. Erosion rates increase with basal shear stress: $a \geq 0$ and by extension,
 158 $n \geq 0$.

159 Conservation of water mass sets the physical meaning of b and c at the reach
 160 ($\sim W$) and basin scale ($\sim L$) [7]. At the reach scale, water discharge $Q = vDW$
 161 is a constant. Furthermore, stability of the channel cross-section imposes a
 162 linear scaling between depth and bankfull width [e.g., 31] $D \sim W$, defining the

163 form of the hydraulic geometry:

$$164 \quad Q \sim W^2, \quad (11)$$

165 so that $b \approx 0.5$. The parameters b and k_w depend on rock mass quality, erosion
 166 process, sediment loading, and hydraulic resistance [16]. The exponent b varies
 167 between $b \approx 0.4 - 0.6$ in alluvial rivers [31, 32] and bedrock rivers [16, 19, 33].
 168 Whereas $b = 0.5$ is a good average, we acknowledge that this exponent is empir-
 169 ical and has inherent variability [34, 35]. Given the limitations in constraining
 170 this variability for Mars, taking $0.4 < b < 0.6$ is a practical choice.

171 Water sources (rainfall, snowfall, groundwater seepage) and sinks (evapo-
 172 ration, permeation, sublimation) set the water mass transported through the
 173 drainage basin. If uniform precipitation dominates the sources, water availabil-
 174 ity increases linearly with drainage area, but the same is false if water enters
 175 the basin as point sources from localized groundwater sapping. If additionally
 176 all water collected in the basin is delivered to the outlet without any losses dur-
 177 ing its transport, or if losses also increase homogeneously with area, the water
 178 inventory in a precipitation-fed system is crudely given by:

$$179 \quad \rho_w \sum Q_i \sim K_{pr} A, \quad (12)$$

180 Precipitation minus evaporation per unit time K_{pr} (kg/m²s) over a drainage
 181 area A increases tributary discharge Q_i , which add up to produce the total
 182 discharge at the outlet (left hand side) that scales linearly with area $Q \sim A$,
 183 with $c = 1$.

184 *2.1.4. Martian climate and the discharge-area exponent c*

185 There is an extensive body of literature that describes the role of spatial
 186 and temporal variability of runoff production through the c exponent [34, 35,

36, 37, 38]. A $c = 1$ exponent requires long-lasting, spatially uniform precipitation events [36], which can correspond either to homogeneous rainfall or snowfall. Non-homogeneous or unsteady rainfall, such as storm events, flooding, or sporadic precipitation yield $c < 1$ [36]. Similarly, topographic controls on temperature [39, 2] produce an uneven distribution of snow on the terrestrial mid-latitudes, implying $c < 1$. However, in high latitude areas on Earth [39, 37], and on the Martian highlands [2] where topography is subdued, snow falls if pressure and temperature are below melting, independently of relief. Thus $c = 1$ is also compatible with snowfall. In the case of groundwater seepage, discharge enters the drainage network spatially concentrated in springs, the number and flux of which does not necessarily increase with basin area [28]. This highlights an independence of discharge in the later, which should yield $c \approx 0$.

In summary, Martian fluvial valley networks in steady-state *must* display concave profiles as imposed by $n > 0$, with a shape consistent with the predictions from equation 3. Fluvial networks consistent with steady-state that are additionally fed by uniform precipitation (rain or snowfall) *should* display $\theta \approx 0.5$, following the scaling arguments presented. We can now quantitatively interrogate the concavity index θ and water mass-balance c characteristics of Martian longitudinal profiles and identify the systems that have substantially modified the landscape around them.

2.2. Evolution from initial conditions

Profile concavity indexes $\theta < 0.45$ are characteristic of systems that still reflect the initial conditions of the landscape. Contrarily, concavity indexes $0.45 < \theta < 0.6$ are consistent with steady-state [16, 17, 18], implying that valley networks were active for a cumulative long period of time. This is true, however, only if the initial curvature characteristics of the landscape were not already initially consistent with $\theta \approx 0.5$.

214 To determine whether concavity indexes yielding $\theta \approx 0.5$ reveal a drainage
 215 basin consistent with steady-state or reflect landscape initial conditions, we
 216 compare our results to the concavity index measured for the background to-
 217 pography [5]. We take the reference background concavity for the appropriate
 218 Noachian terrain each valley incises (supplement) [5] as proxy for landscape ini-
 219 tial conditions, so that there is landscape modification if $\theta > \theta_{bkgrd}$ [5]. For the
 220 valleys showing $\theta > \theta_{bkgrd}$, we additionally assess this condition by comparing
 221 curvature far away from the drainage basin area, in the basin area, and in the
 222 valley network profile, using the MOLA-derived curvature raster (supplement).

223 **3. Comparison of valley network profiles and steady-state model so-** 224 **lutions**

225 *3.1. Longitudinal profile extraction*

226 We extracted the main stem longitudinal profile of 62 valley networks (sup-
 227plementary tables 1 and 2). After selecting valley network targets of different
 228 locations, morphological characteristics, and timing of activity, we manually
 229 mapped the streamline of each network’s main stem. Although a previous
 230 global map of valley streamlines exists [8], our own mapping efforts using a
 231 combination of MOLA, THEMIS, and CTX mosaics provides higher resolution
 232 streamlines (figure 1).

233 For profile extraction we use MOLA PEDR altimetry point data [6], instead
 234 of gridded MOLA/HRSC DEM data [40]. Although the nominal resolution for
 235 the MOLA gridded DEM is a few hundred meters, the spacing between laser
 236 points along a valley is variable and often up to a few kilometers. Interpolation,
 237 DEM stitching, as well as other errors can also introduce uncertainty in the
 238 MOLA DEM. To minimize these effects, we select the MOLA altimetry points
 239 that are within 100 m of mapped valley network stream lines (figure 1), ac-

Figure 1: Mapping, extraction, filtering, and non-linear best fit to the longitudinal profile of Tader valleys. (a) THEMIS mosaic overlain with the manually mapped main stem streamline (orange) compared to streamlines from Hynek et al., 2010 [8] (green) for Tader valleys. (b) Box inset showing a CTX mosaic overlain with MOLA for streamline comparison (see arrows), and the extraction of MOLA PEDR data (dots) within 100 m of the streamline. (c) MOLA PEDR longitudinal profile of Tader valleys (red crosses) and Mean Moving Filtered profile (MMF, dashed line). (d) Best fit of the MMF data to equation 13, with RMS definition.

counting for the ≈ 100 m MOLA laser footprint [41]. We then filter the profile using a Moving Mean Filter (MMF) with a window of 5 altimeter points. Profile disturbances much smaller than the basin length (e.g., most craters, faults, dunes) do not affect our concavity analysis.

3.2. Non-linear regression and misfit evaluation

We characterize the shape and curvature of valley network profiles fitting the following non-linear equation to the normalized form of each profile:

$$z_* = a_f/b_f - a_f/b_f x_*^{b_f}, \quad (13)$$

248 This equation is formally equivalent to the integration of Hack’s second law
 249 2, the solution to the stream-power law 4, and the zero-uplift solution to the
 250 alluvial landscape evolution equation 6, with $b_f = 1 - h\theta$, and a_f/b_f relating to
 251 the steepness index K_s as appropriate. Note that our approach is different from
 252 the extraction of θ directly from Flint’s law (equation 1); equation 13 cannot be
 253 linearized using logarithms and requires the use of non-linear fits to the data.
 254 To extract the concavity index θ we set $1/h \approx 0.74$ [5, 21, 23]. From best fits we
 255 extract the combination of parameters that minimize the *RMS* misfit between
 256 each profile and the equilibrium curve predicted in equation 13. Figure 1 shows
 257 an example of a valley network profile extraction and non-linear fit.

258 There are two advantages to this technique. First, this method is inde-
 259 pendent of drainage area A . Other studies rely on the present topography to
 260 delineate drainage area information, required for extracting θ through Flint’s
 261 law [22, 23, 30]. Extracting the drainage area is challenging for Martian valley
 262 networks [22, 23, 30] due to post-emplacement basin alteration [5] (*Bahia et al.*,
 263 2020 (*submitted*)), which results in unrepresentative drainage area values. Our
 264 study relies on main stem length, which is much easier to extract than drainage
 265 area. Second, our approach is more sensitive to curvature than other techniques
 266 [21, 23], providing a better estimate of θ as well as measure of the goodness of
 267 the fit (*RMS*) and error bounds.

268 We chose an $RMS = 0.1$ to mark a goodness threshold, with profiles with
 269 $RMS > 0.1$ discarded as too irregular to be consistent with prolonged fluvial
 270 activity. In profiles with $RMS < 0.1$ we retrieve the concavity index θ (table 1),
 271 with all our fit results presented in supplementary table 1. Profiles that indicate
 272 fluvial landscape modification are regular ($RMS < 0.1$) and display concavity
 273 indexes $\theta > \theta_{bgnd}$. We chose a threshold $\theta = 0.45$ to identify those valley
 274 networks consistent with steady-state, provided that their concavity index was

(1) larger than the statistical background concavity [5] and (2) different from the concavity exhibited in MOLA gridded curvature data (supplement).

The error $\delta\theta$ (supplementary table 1) includes the statistical errors of the a_f and b_f parameters extracted from fitting equation 13 as well as the empirical variability for Hack’s exponent on Mars Δh [23]:

$$\delta\theta = \frac{\delta b_f - \Delta h \theta}{h}, \quad (14)$$

Similarly, the upper and lower bounds on c reported are obtained using the error bounds in θ and $0.4 < b < 0.6$, using that:

$$c = \frac{\theta}{(1 - b)}, \quad (15)$$

3.3. Supportive observational characterization of drainage-basin morphology

Morphological analysis of valley networks, including drainage density, stream order, and valley width and length are commonly used on Mars to infer past climate and precipitation conditions [24, 25, 8]. We seek to compare inferences from valley morphometry with our concavity results, focusing our attention to three valley networks with representative profile shapes. Using image data from the High Resolution Stereo Camera (HRSC, 15 to 25 m/pixel) and Context Camera (CTX, 5 m/pixel), we compare the main valley length and width, the drainage density, and the maximum Strahler number of the valley networks considered (figure 2).

Whereas valley length is related to drainage area through Hack’s law, width increases with discharge [25, 42]. Mathematical considerations show that the Strahler number of a network scales like the logarithm of the number of first order tributaries [43, 42], suggesting that older networks with larger water inputs should develop higher stream orders [8] (as long as threshold stresses are

299 achieved). Drainage density increases with time-integrated fluvial activity in
 300 the basin [24, 25, 8], depending on the runoff generation mechanism and the
 301 threshold for incision.

302 Valley length measurements are calculated from the mapped streamlines
 303 using the ArcMap 10.2.1 'Calculate Geometry' function, and we use CTX images
 304 to estimate valley width. We determine drainage density values from ArcMap
 305 'Spatial Analyst - Line Density Tool'. Strahler numbers are obtained from
 306 Hynek et al. [8].

307 **4. Results and evaluation of longitudinal profiles: Modeling and ob-** 308 **servation insights**

309 *4.1. Concavity and steady-state of valley networks*

310 We identify three main categories of valleys (figure 2): (1) Those with regular
 311 profiles $RMS < 0.1$ and concavity indexes larger than background $\theta > \theta_{background}$,
 312 exemplified by Naktong Valles. These systems have concave profiles charac-
 313 teristic of long-term landscape modification. (2) Valley networks with regu-
 314 lar profiles ($RMS < 0.1$) that display concavity indexes inconsistent with the
 315 long-term fluvial modification of the landscape ($\theta < \theta_{background}$). Arda valles
 316 ($RMS < 0.1$, $\theta = -0.3$) is the reference example for this group. (3) Valley
 317 networks that are too irregular ($RMS > 0.1$), exemplified by Pallacopas Vallis,
 318 cannot be described successfully with models of fluvial erosion.

319 From the sixty-two valleys analyzed, Cusus, Himera, Al-Qahira, Evros, Nak-
 320 tong, and Tisia Valles have longitudinal profiles with $\theta > 0.45$, $\theta > \theta_{bkgd}$
 321 (supplement, figure 4). These systems have both significantly modified their
 322 surrounding landscape and achieved profile shapes consistent with steady-state
 323 (table 1). Of the remaining valley networks analyzed, forty-seven display regular
 324 profiles ($RMS < 0.1$) with concavities not consistent with long-term fluvial ero-

Figure 2: Valley network profiles representative of the three types: Nakdong (left), Arda (middle) and Pallacopas Vallis (right). Valley network elevation profile data (dashed lines) overlapped by steady-state best fit model results (red solid line). Horizontal and vertical axes are normalized to the distance along the valley and the total topographic drop respectively.

325 sion [16, 19, 18]. These systems are fully (i.e., Licus Valles, Arda Valles, Parana
 326 Valles), or partially convex, with presence of knickpoints (i.e., Dubis Vallis), or
 327 markedly stepped sections (e.g., Warrego Valles, Indus Valles, Auqakuh Valles).
 328 Finally, nine valley networks have irregular profiles ($RMS > 0.1$) (i.e., Pallaco-
 329 pas Valles). The RMS and concavity index θ of the whole dataset are shown
 330 in figure 3 and in supplementary table 1.

331 The statistics of our concavity indexes are broadly comparable with previous
 332 work. For example, Penido and others [23] found no consistent form for valley
 333 network profiles, ranging from concave to convex, with an average concavity
 334 index $\theta < 0$. Aharonson et al. [20] found concavity indexes $\theta < 0.3$, consistent
 335 with Caprarelli and Wang [22], who found $\theta < 0.3$. Our work, which considers
 336 a much larger sample size, finds an average $\theta = -0.16$ with significant inter-
 337 valley variability. This convex index reflects inherited topography, indicating
 338 that the duration of the fluvial activity was short compared to the landscape
 339 equilibrium timescale. This can indicate shorter episodes in a friable substrate,
 340 or much longer episodes in competent bedrock.

Figure 3: Concavity index θ (horizontal axis) and root mean square error between profile data and model fit RMS (vertical axis) in left and right panels. Valley networks colored green are consistent with steady-state fluvial erosion (see table 1). Systems in purple are not consistent with fluvial steady-state erosion but have regular profiles $RMS < 0.1$. Systems with $RMS > 0.1$ are colored in red. The right shows a zoomed image of the black box, with the dashed line marking the cutoff $\theta = 0.45$ set in table 1, and the blue line marking the average background concavity for Noachian terrain $\theta_{bkgnd} = 0.39$.

4.2. Water source: point source or precipitation?

Equation 15 introduces a relationship between concavity index θ and area-discharge exponent c . The interpretation of c is only strictly true if the valley network is consistent with steady-state, but it can be extended to systems slightly out-of-equilibrium. Table 1 compiles the subset of our data containing regular profiles ($RMS < 0.1$) and concavity above that of the background landscape, as well as those valleys consistent with steady-state $\theta > 0.45$.

Valley networks consistent with steady-state concavities are also coherent with water sources and sinks distributed largely uniformly over the drainage basin ($c \approx 1$): this includes rain or snowfall as sources, and evaporation, sublimation, and/or uniform seepage as sinks. None of the valley networks in table 1 display point sources of water ($c \approx 0$), implying that the runoff did not originate from springs.

Table 1: Name, location (lat/long), fit goodness RMS , concavity index θ , and discharge-area exponent c for valley networks consistent with steady-state ($\theta > 0.45$) and some degree of landscape modification ($\theta > \theta_{bkgrd}$). Interpretation type 1 means precipitation and losses were uniformly distributed around the basin area ($c \approx 1$). Type 2 is mostly uniform precipitation and losses ($c < 0.95$), and type 3 is non-uniform precipitation or losses ($c < 0.9$).

Name	lat	long	RMS	θ	θ_{bkgrd}	c	interpretation
$\theta \approx 0.5$							
Cusus Valles	14.30	50.50	0.08	0.53	0.38	1	Type 1
Himera Valles	-21.40	-22.80	0.07	0.57	0.36	1.1	Type 1
Al-Qahira Valles	-18.20	162.50	0.06	0.5	0.38	1	Type 1
Evros Valles	-12.60	13.90	0.04	0.54	0.38	1.1	Type 1
Naktong Valles	5.20	32.90	0.04	0.47	0.38	0.94	Type 2
Tisia Valles	-4.96	44.30	0.05	0.46	0.38	0.91	Type 2
$0.45 > \theta \geq \theta_{bkgrd}$							
Protva Valles	-29.00	-60.60	0.04	0.39	0.39	0.78	Type 3

354 4.3. Geomorphological Analysis of Naktong Valles, Arda Valles and Pallacopas 355 Vallis

356 We contrast the morphological analysis results for the three profile end-
357 members (section 4.1) with our concavity findings. Figure 4 shows the drainage
358 density, main valley length, and Strahler number of Naktong, Arda, and Palla-
359 copas Valles.

360 Naktong Valles (figure 4a) originates south of Janssen crater at an altitude
361 of 1813 m and width of ≈ 2090 m, and terminates at an altitude of -297 m
362 with a width of ≈ 5000 m south of Argo crater. Naktong valles' longitudinal
363 profile is smooth ($RMS < 0.1$) and concave, consistent with fluvial steady-
364 state ($\theta = 0.47 \pm 0.03$). This valley network has the largest main stem length
365 (1170.8 km), drainage area (0.046 km^{-1}) and Strahler number (6) of the three
366 valleys described here. All these values are considerably larger than average
367 for the Martian valley networks [8]. Figure 4A shows the dendritic planform of
368 Naktong Valles, with river terraces identified in the downstream reaches of the
369 system (see e.g., figure 4A).

370 Arda Valles (4B), displays a regular profile ($RMS < 0.1$), but concavity
371 index ($\theta = -0.3 \pm 0.08$) inconsistent with steady-state. It is the shortest main

Figure 4: CTX imagery overlapped with valley networks streamlines showing main stem length, drainage density, and Strahler number for (A) Naktong Vallis with potential river terraces (A), (B) Arda Valles, and (C) Pallacopas Vallis.

stem of the three systems investigated (170.3 km). Compared to Naktong, Arda Valles has a lower drainage density (0.017 km^{-1}), Strahler number (4) and lacks observable river terraces. The drainage density of Arda Valles is comparable to the average value for valley networks incising Noachian terrains (0.0115 km^{-1} [8]). The Strahler number reported is higher than average [8] (≈ 1.5), and so is the length of the main stem (average 13.1 km). Arda Valles' source is located at an elevation of 59 m, and it terminates in an unnamed basin (altitude of -1861 m), flowing from SW to NE. There is little difference between source width ($\approx 1900 \text{ m}$) and termination width ($\approx 1990 \text{ m}$). Similar to Naktong, Arda Valles displays a well-preserved dendritic valley planform.

Figure 4C shows Pallacopas Vallis' distinctive trellis planform, heavily de-

383 graded and disjointed in areas. Although Pallacopas has a much longer main
 384 stem (555.3 km) than Arda Valles, its drainage density (0.016 km^{-1}) and
 385 Strahler number (3) are lower. The main stem of Pallacopas Vallis (figure 4C)
 386 has a source altitude of 619 m and width of ≈ 6200 m, termination altitude of
 387 197 m and terminal width of ≈ 6940 m. Our results yield $\theta = -6 \pm 3$ with an
 388 $RMS = 0.21$. These observations are coherent with the concavity results.

389 5. Mature valley networks and water sources: discussion and impli- 390 cations

391 5.1. Steady-state valley network distribution

392 Figure 5 displays our results on a global map of Mars. Valley networks
 393 with $\theta \approx 0.5$ lie mostly along the narrow topographic belt linking the Noachian
 394 Highlands with Arabia Terra, as well as Aeolis outside of this corridor (sup-
 395 plement). These systems are consistent with uniform precipitation (snow or
 396 rain) and uniform water losses (table 1, $c \approx 1$). Protva valles ($\theta = 0.39$) also
 397 produced landscape modification. We find a discharge-area exponent $c = 0.78$
 398 for Protva, possibly indicating non-uniform precipitation such as contributions
 399 from localized storms and springs, and/or with localized losses in the network.

400 Valley networks with $RMS < 0.1$ and $\theta < \theta_{bkgrd}$ failed to create an ero-
 401 sional drainage basin. These examples comprise 47 of 62 valleys, indicating that
 402 the majority of valley networks only produced minimal landscape modification.
 403 Thus, the duration of fluvial erosion was much shorter than the landscape equi-
 404 librium timescale. These characteristics represent an important distinction with
 405 terrestrial river valleys.

406 Finally, valley networks with irregular profiles ($RMS > 0.1$) comprise 9
 407 out of 62 valleys analyzed. They either have been substantially modified by
 408 tectonic processes without visible surface expression, or were not carved by

Figure 5: Global map of Mars (MOLA) and valley networks streamlines [8]. Red crosses show valleys with irregular profiles ($RMS > 0.1$). Black crosses show valleys with little fluvial modification ($RMS < 0.1, \theta < \theta_{bkgd}$) and concavity comparable to initial conditions. Triangles show valleys with regular profiles, concavity differing from background suggesting landscape modification but not steady-state ($RMS < 0.1, 0.45 > \theta > \theta_{bkgd}$). Stars show valleys with regular profiles consistent with steady-state concavities $RMS < 0.1, \theta > 0.45$, and yellow and green stars indicate discharge-area exponents $c \approx 1$ and $c < 1$). Areas numbered 1 to 3 are described in section 5.1.1.

409 fluvial processes (*Grau Galofre et al., submitted*). The majority of irregular
 410 valleys are located following the Argyre-Margaritifer-Oxia Palus belt, draining
 411 into the Uzboi-Ladon-Morava outflow system, and in Ismenus Lacus.

412 5.1.1. Results by drainage basin

413 The proximity between “developed” (stars, figure 5) and “underdeveloped”
 414 (triangles and black crosses) valley networks indicates that proximal valleys can
 415 be in different stages of landscape evolution. Here we discuss three examples
 416 (figure 5, areas 1-3), of which two are shown in figure 6 (context for all valley
 417 networks is in supplementary table 2). The first case (1) is the Loire-Samara-
 418 Parana system, of which only one tributary (Himera valles, $\theta = 0.57 \pm 0.02$) is
 419 consistent with fluvial steady-state. The three main stems in the basin display

420 concavity indexes far from steady. Parana valles' profile is smooth but convex
 421 ($\theta = -0.37 \pm 0.06$), Loire valles' profile is convex and highly irregular ($\theta =$
 422 -0.5 ± 0.1 , $RMS = 0.13$), and Samara valles' is smooth and slightly concave
 423 ($\theta = 0.2 \pm 0.01$).

424 Parana valles drains into Parana basin, a chaotic basin assumed to be a relict
 425 paleolake, from which the main stem of Loire valles emerges [44]. Just before
 426 its outlet, Loire valles merges with the main stem of Samara valles to drain
 427 into Morava valles, part of the Uzboi-Ladon-Morava outflow channel system
 428 [45]. When interrogating the longitudinal profile of a combined Parana-Loire
 429 main stem, we find an overall irregular ($RMS > 0.1$) and concave profile ($\theta =$
 430 0.3 ± 0.1), suggesting that the combined system responded to a single base-level
 431 elevation set by Morava valles. This combined profile shows a sharp change in
 432 curvature at Parana basin, indicating that this system was not well integrated
 433 and it did not evolve synchronously to steady-state. The change of curvature
 434 located in Parana basin and the volume of alluvium accumulated [45], moreover,
 435 could indicate the presence of a dam.

436 Another case of interest is the Naktong-Scamander-Mamers system (NSM,52)
 437 shown in figure 6 (a and b), one of the largest drainages on Mars [46]. Including
 438 Tisia valles, the basin elevation drops from 2,500 m at the headwaters of Tisia
 439 to -3,500 m at the lowest point of Mamers. Activity in Naktong, Scamander,
 440 and Mamers vallis is dated from the early Hesperian period [47, 46], whereas
 441 activity in Tisia valles has not been dated. The four valley networks drain in
 442 the same overall direction (SE-NW) and are situated in close spatial proxim-
 443 ity, but display distinct planforms and profiles. Mamers and Scamander valles
 444 have concavity values of $\theta = 0.20 \pm 0.04$, and $\theta = -0.79 \pm 0.1$ respectively, far
 445 from those reported for Naktong ($\theta = 0.47 \pm 0.03$) and Tisia ($\theta = 0.46 \pm 0.02$),
 446 which are both consistent with steady-state. Mamers profile shows multiple

Figure 6: Integrated basin analysis for the Tisia-Naktong-Scamander (TNS) and the Evros-Mosa (EM) systems. (a) shows the planform (THEMIS + MOLA), network streamlines [8] and our own streamline (yellow) for TNS, with closeup (right) showing the Tisia-Naktong proposed junction. Junctions are marked using black arrows. (b) TNS Longitudinal profiles (including Mamers), x axis is distance (km), y axis is elevation (m). (c) planform morphology (THEMIS + MOLA) of the EM system, showing the proposed junction point with an arrow. (d) longitudinal profile of Mosa and Evros vallis.

447 slope reversals that are hardly consistent with fluvial erosion (figure 6b), sug-
 448 gesting instead erosion or reworking by glacial processes and mass wasting [48].
 449 Comparing Mamers and Naktong valleys profiles and morphology, we find the
 450 evidence lacking to make a case for their belonging in the same fluvial drainage
 451 basin.

452 In contrast, Scamander valley is connected with Naktong valley's outlet through
 453 a sedimentary basin (figure 6). In spite of the spatial proximity, the differences
 454 between Naktongs and Scamanders concavity index suggest that the total time
 455 of activity was much longer for Naktong than Scamander. This result is sup-
 456 ported by Scamander's sparse network with small stream orders and a large
 457 main stem. The combined observations support the formation hypothesis in-
 458 volving flooding or basin overflow [47], resulting in short-lived fluvial activity in
 459 Scamander.

460 Tisia valley has a smooth concave profile consistent with steady-state ($\theta =$
 461 0.46 ± 0.02) and discharge-area exponent indicating steady, uniform precipita-
 462 tion $0.76 \leq c_{Tisia} \leq 1.14$ similar to that of Naktong $0.78 \leq c_{Naktong} \leq 1.17$.
 463 Although Tisia is much shorter, the comparable morphology between Tisia and
 464 Naktong (similarly sized tributaries and large network stream orders) suggest
 465 that the two valleys responded to analogous environmental conditions of uni-
 466 form precipitation. Moreover, topographic data shows a possible connection
 467 between Tisia valley and a Naktong tributary (figure 6), suggesting that Tisia
 468 and Naktong may have been one integrated drainage system.

469 The last basin we consider is the Evros-Mosa system (figures 53, 6c and d).
 470 This is an extensive (56,000 km² [5]) drainage system located in western Terra
 471 Sabaea [49, 22], with a total elevation drop from $\approx 2,000$ m down to ≈ -100
 472 m. Activity in the valleys is dated Late Noachian to Early Hesperian [47, 46].
 473 Although the proximity between Mosa's outlet and an Evros' tributary headwa-

ters suggests a connection existed [9], their profiles are very disparate (figure 6). Evros valles' profile is smooth and concave ($\theta = 0.54 \pm 0.03$, $RMS = 0.04$), whereas Mosa valles' profile is convex $\theta = -0.9 \pm 0.3$ and more irregular ($RMS = 0.08$). The differences in profile between Mosa and Evros are also reflected in their morphology: Mosa shows smaller tributary densities and stream order than Evros [8], as well as discrepancies in main stem depth and width between Mosa's outlet and the point of junction with Evros (black arrow). Given the lower concavity and tributary density, we infer that Mosa valles was active for a much shorter period than Evros valles, either incising only during a reactivation of the Evros system or lacking a later period of activity.

Our estimation of the area-discharge exponent $1.36 \leq c \leq 0.91$ suggests uniform precipitation over the Evros basin, in agreement with a terminal episode of intense fluvial activity [9]. The climate transition suggested by Howard et al., 2005 [9], however, cannot be validated from the shape of Evros valles. Profile knickpoints, which should appear in response to a climate transition [16, 50] from an arid climate (lower concavity) to a wetter climate (higher concavity) [50], are absent from the profile. Evros therefore was active for long enough under the new climate conditions to achieve steady state, or was not affected by a climatic change.

It is important to note that previous studies report different concavity exponents for Evros valles, both among them and compared with ours: $\theta = -0.61$ [21] and $\theta = 0.23$ [22]. These discrepancies can be attributed to differing choices of main stems [21] and different interpretations of drainage area boundaries, which the same authors recognize to be problematic [22], as well as the sensitive dependence of their methodology on derivatives of the MOLA gridded DEM [22]. Due to the sensitivity of Flint's law to drainage area, large uncertainties in the later can yield vastly different and possibly unreliable results.

501 *5.2. Distribution with respect to surface tectonics*

502 All valley networks with profiles consistent with fluvial steady-state (figure
503 7, black stars) are in areas with sparse surface structures [51]. Valley networks
504 in regions with high density of reported superficial faults [51], such as Warrego
505 Valles, are often not in steady-state and display abrupt changes in profile slope,
506 stepped sections, and knickpoints. Although this is consistent with observations
507 of terrestrial river valleys in regions of rapid uplift or sudden base level fall [16],
508 more work is necessary to establish a causal relationship.

Figure 7: Global map of Mars (MOLA) overlapped by the surface tectonic structures as mapped by [51], showing the location of the valley networks in our study, their classification as described in the text and the caption. Note the lack of regular valley networks close to significant surface tectonic expressions.

509 *5.3. Comparison of theoretical and observational insights on valley network*
510 *morphologies.*

511 Here we discuss network maturity for the three end-member valleys discussed
512 in section 5.1 (Naktong, Arda, and Pallacopas) comparatively using drainage
513 density, Strahler order, and profile concavity results. The drainage density of
514 Naktong Valles is the highest among the three systems analyzed, consistently
515 with it having $\theta \approx 0.5$. However, Naktong’s drainage density is an order of
516 magnitude below the highest density values reported, e.g., for Ravius Valles.
517 Ravius Valles’ concavity is, however, far from steady-state values $\theta \approx 0.09 \pm$
518 0.02 , $RMS = 0.02$, suggesting that care should be taken when making a case for
519 valley maturity solely on the basis of drainage density. Additionally, whereas
520 valley networks consistent with steady-state concavities have Strahler orders
521 much larger than average (above 4 in all cases), the reciprocal is not true: Some
522 of the highest Strahler order systems (> 5), such as Loire or Parana Valles,
523 have convex or irregular profiles that are inconsistent with fluvial steady-state
524 (supplement).

525 Naktong displays an increase in width from source to termination (section
526 4.3) typical of a fluvial system formed via surface runoff and indicative of an in-
527 crease in discharge down-slope. Naktong’s higher-than-average drainage density
528 and Strahler number [8] are consistent with greater water fluxes and/or a longer
529 activity span. Additional evidence of sustained fluvial activity within Naktong
530 Valles is the presence of possible river terraces (figure 4A and A’), potentially
531 indicative of periodic flooding and incision.

532 Arda Valles has a convex profile inconsistent with fluvial steady-state ($\theta =$
533 -0.3 ± 0.08). Arda enters an unnamed basin part of the Uzboi-Ladon-Morava
534 system, with no visible alteration of the initial basin rim topography (figure
535 4B), supporting our results. The low drainage density and Strahler number of

536 this valley network also agree with a lack of sustained fluvial activity. Addi-
 537 tionally, Arda Valles shows a negligible increase in width from source to ter-
 538 mination, indicating it experienced a remarkably small downstream discharge
 539 growth despite having a Strahler number equal to 4. This apparent lack of
 540 downstream cumulative discharge may be a consequence of substantial evap-
 541 oration, water seepage, or different timing of tributary activity. Finally, the
 542 presence of a fault cross-cutting the termination of Arda Valles indicates that
 543 this area was locally tectonically active post-emplacement of the valley net-
 544 work (Late Noachian-Early Hesperian [47]). However, this activity appears to
 545 have caused insignificant alterations to the basin-scale valley profile, given the
 546 otherwise remarkably smooth profile (figure 4).

547 The longitudinal profile of Pallacopas Vallis is irregular ($RMS < 0.1$) with
 548 large undulations (figure 2). Whereas degradation may explain to some extent
 549 why Pallacopas Vallis does not display a regular profile, its disconnected stem
 550 far, from surface tectonics (figure 7), is also hardly consistent with formation via
 551 surface runoff. Pallacopas Vallis displays a low drainage density and Strahler
 552 number (figure 4). Combining these factors with its high southern latitude
 553 and the presence of profile reversals, the formation of Pallacopas Vallis is more
 554 consistent with a subglacial origin (*Grau Galofre et al., submitted*).

555 6. Conclusions

556 In this study we use an observational and modeling approach to address two
 557 questions: Were valley networks active for long enough to significantly alter the
 558 landscape and achieve steady-state? What water sources are most consistent
 559 with morphology and profile shape? To proceed, we use a generalized solution
 560 describing steady-state river profiles to make predictions for the form of valley
 561 networks in equilibrium [17]. We then build the physical intuition necessary to

562 interpret concavity and the origin and water source to the basin.

563 We use MOLA laser altimeter point PEDR data and high resolution val-
564 ley network streamlines to derive valley longitudinal profiles. To interrogate
565 each individual profile, we perform a non-linear fit directly between profile and
566 steady-state solution. This novel technique enables the extraction of the con-
567 cavity index without measuring the drainage area, which is problematic to es-
568 timate for the valley networks. Our results reveal that six valley networks out
569 of 62 analyzed are consistent with fluvial steady-state: Naktong, Evros, Tisia,
570 Al-Qahira, Cusus, and Himera valleys. Four of these valleys are clustered in
571 the corners of Syrtis Major-Arabia-Sinus Sabaeus regions. Another 9 valley
572 networks show irregular profiles with undulating or disrupted sections, located
573 mostly following the Uzboi-Ladon-Morava megasystem from the south of Ar-
574 gyre into the lowlands. The vast majority of the valleys analyzed (47 out of
575 62) did not achieve any substantial basin development, indicating the lack of
576 protracted fluvial activity at a global scale.

577 Our findings yield disparity in concavity indexes of valley networks belonging
578 in the same integrated basins, indicating different stages of landscape evolution
579 and lack of synchronous valley development. Our results highlight the global
580 lack of protracted fluvial activity on Mars, but identify for the first time the
581 presence of valley networks consistent with steady-state. The Naktong and
582 Evros basins, in particular, should be considered as systems with long-term
583 fluvial activity.

584 **Supplementary Information** This manuscript contains supplementary in-
585 formation consisting on supplementary methods, supplementary table 1, and
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Correspondence Correspondence and requests for materials should be ad-
dressed to Anna Grau Galofre (email: agraugal@asu.edu).

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