Topographically derived maps of valley networks and drainage density in the Mare Tyrrhenum quadrangle on Mars

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[1] A novel, automated technique for delineating Martian valley networks from digital terrain data is applied to the Mare Tyrrhenum quadrangle on Mars, yielding a detailed map for the entire quadrangle. The resultant average value of drainage density for the Noachian part of the quadrangle is $D \approx 0.05$ km^{-1}, an order of magnitude higher than the value inferred from a global map based on Viking images, and comparable to the values inferred from the precision mapping of selected focus sites. Valleys are omnipresent in Noachian terrain even outside the "highly dissected" Npld unit. This suggests fluvial erosion throughout the Noachian, implying widespread precipitation. The map of continuous drainage density is constructed to study spatial variations of D. This map reveals significant variations in degree of dissection in Noachian on scale of >100 km. These variations do not correlate with any terrain parameter and their origin requires further study. Citation: Luo, W., and T. F. Stepinski (2006), Topographically derived maps of valley networks and drainage density in the Mare Tyrrhenum quadrangle on Mars, Geophys. Res. Lett., 33, L18202, doi:10.1029/2006GL027346.

1. Introduction

[2] Valley networks (VN), discovered in 1971 by the Mariner 9 spacecraft, are geomorphic features on Mars exhibiting some visual resemblance to terrestrial river systems. This similarity led to a suggestion [Masursky, 1973; Milton, 1973] that they are remnants of once active drainage networks. Carr [1995] and Carr and Chuang [1997] has mapped over 800 VN throughout the entire surface of Mars based on the Viking Orbiter images. They have found that great majority of VN are located in Noachian terrain. The predominance of VN in this ancient terrain raises the possibility that climate on Noachian Mars was significantly warmer and wetter than what is presently observed, and that VN formed by rainfall-fed runoff erosion.

[3] However, significant morphometric differences exist between VN and mature terrestrial drainage systems. VN often display widely spaced tributaries with alcove-like headscarps [Pieri, 1980], constant valley width downstream [Goldspiel et al., 1993], short, stubby tributaries [Baker and Partridge, 1986], flat or irregular longitudinal profiles [Aharonson et al., 2002], and U-shaped cross-sections. These features are similar to those observed at some headwater canyons in the Colorado Plateau and are attributed to erosion due predominantly to groundwater sapping [Laity and Malin, 1985] rather than runoff. On the larger scale, the VN, as mapped by Carr, lack spatial integration, so dissected areas are commonly separated from each other by undissected areas of similar or larger size. As a result, Carr and Chuang [1997] reported that the drainage density of Noachian terrain, $D_{\mathrm{Noach}} = 7 \times 10^{-3}$ km^{-1}, is much lower than $D_{\mathrm{terr}} \sim 10^{-1}$ km^{-1} of a typical, runoff-eroded terrestrial landscape calculated from Landsat images degraded to the resolution of Viking images. These observations gave rise to a hypothesis that VN originated primarily by means of groundwater sapping erosion [see, for example Malin and Carr, 1999]. The potential implication of this hypothesis is that no warm and wet climate on early Mars is required to account for the sapping origin of VN [Squyres and Kasting, 1994], providing that groundwater was recharged by hydrothermal circulation [Gulick and Baker, 1990].

[4] On the other hand, the runoff origin of VN is supported by observations such as branching, dendritic patterns, origin near dividing ridges [Irwin and Howard, 2002; Craddock and Howard, 2002; Hynek and Phillips, 2003; Stepinski and Collier, 2004], consistency with crater degradation [Forsberg-Taylor et al., 2004], and significant erosion requiring aquifer recharge [Grant, 2000]. In addition, recent field work by Irwin et al. [2006] puts in doubt the predominantly sapping origin of Colorado Plateau canyons, raising the possibility that unique features of these canyons, as well as similar features of VN on Mars, may not be indicative of sapping erosion after all. Finally, the notion that dissection of Noachian terrain by VN results in low values of D stems from the original global mapping of VN by Carr. Subsequent, more detailed mapping of selected sites [Hynek and Phillips, 2003; Stepinski and Collier, 2004; Ansan and Mangold, 2006] yield $D \sim 10^{-1}$ km^{-1}, roughly comparable with terrestrial values as calculated by Carr and Chuang [1997].

[5] The purpose of this paper is to provide a detailed map of VN and D in the Mare Tyrrhenum quadrangle (MC22), a region at least an order of magnitude larger than the largest site for which a detailed map of VN is currently available. We take advantage of the two new techniques that recently have become available. First, Molloy and Stepinski [2006] and I. Molloy and T. F. Stepinski (Automatic mapping of valley networks on Mars, submitted to Computers and Geophysics, 2006, hereinafter referred to as Molloy and Stepinski, submitted manuscript, 2006) have developed an algorithm for automatic mapping of VN from digital elevation models (DEMs) data. For a large region like MC22 manual mapping is impractical because of the required labor and the questions regarding consistency and subjectivity of

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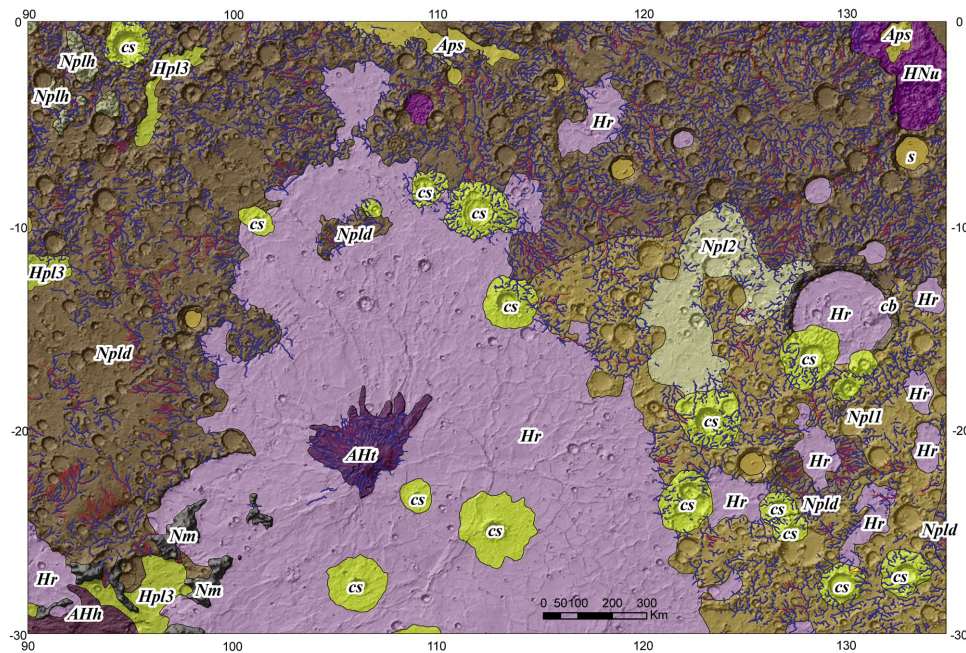
Figure 1. Map of valley networks in the Mare Tyrrhenum quadrangle on Mars. Blue lines indicate VN mapped in this study, red lines indicate VN mapped by *Carr* [1995] and *Carr and Chuang* [1997], and black lines indicate boundaries between geological units, which are marked by different colors.

the results. We use the automatic mapping followed by manual inspection to derive the detailed map of VN in the MC22 region. Second, *Tucker et al.* [2001] have proposed a new and general method to define and measure the drainage density using the DEMs. Their method provides a means for mapping variability of D over large areas. We have applied this new technique to construct a map of D in the MC22 region. Together, these two techniques enable an unprecedented quantitative description of drainage properties on Mars on regional, and eventually, the global scale. The maps of VN and D generated for the MC22 region suggest omnipresent fluvial erosion in Noachian, indicating the important role for surface runoff.

2. Mapping Valley Networks

[6] The MC22 quadrangle (90°E – 135°E, 0°S – 30°S) is centered on Hesperia Planum, with two extensive Noachian regions, Terra Tyrrhenum and Terra Cimmeria, on its west and east flanks, respectively. The DEM for MC22 site is constructed from the Mars Orbiter Laser Altimeter (MOLA) Mission Experiment Gridded Data Record (MEGDR) [*Smith et al.*, 2003] that has resolution of 1/128 degree, resulting in the DEM with dimensions of 5760×3840 pixels. The spatial resolution of the MEGDR (463 m/pixel at the equator) is actually worse than the resolution of images used by Carr to map the VN, but the ability of topography data to outline even shallowly incised drainage pathways and the consistency of automatic mapping result in a much more detailed map.

[7] The mapping algorithm [*Molloy and Stepinski*, 2006, also submitted manuscript, 2006] is based on terrain morphology, and its goal is to map VN in agreement with visual evidence. It calculates the topographic planar curvature, κ, for each pixel in the DEM. The κ influences the divergence/

convergence of potential flow; $\kappa > 0$ flags segments of terrain where flow converges, whereas $\kappa < 0$ flags segments of terrain where flow diverges. Thus, the VN are identified by relatively large positive values of the κ. Landforms other than VN, but also characterized by $\kappa > 0$, are filtered out by a series of morphologic operators and masks. Excellent agreement between automated and detailed manual maps was established [*Molloy and Stepinski*, 2006, also submitted manuscript, 2006].

[8] Application of this algorithm to the MC22 results in 172,396 km of mapped VN. We have carefully inspected the machine-delineated VN and filtered out those that we have judged to be false detections, primarily κ-positive landforms located at the foothills of ridges at the Hesperia Planum. The final map is shown on Figure 1, the blue lines indicate 142,885 km of VN mapped by our procedure, and the red lines indicate 25,447 km of VN mapped by Carr. Thus, overall, we have mapped 5.6 times more valleys than are present in the Carr map. Table 1 gives a comparison of D values between our map and the Carr map, broken into separate geological units. On both maps the great majority of VN are located in Noachian terrain. For Noachian units the values of D, calculated on the basis of our map, are roughly an order of magnitude higher than the values calculated on the basis of the Carr map, however, the difference is the smallest for the Npld unit, already interpreted as "dissected." We have also found valleys in the cs unit adjacent to Noachian terrain, but not on the cs unit adjacent to Hesperian terrain. Tyrrhena Patera (AHt), located in the middle of Hesperia Planum, is also heavily dissected. Values of D for the Hesperian units are an order of magnitude smaller than the values of D for the Noachian units. Moreover, inspection of Figure 1 reveals that most "Hesperian" VN are protrusions from larger VN systems located in Noachian terrain; slight adjustment of boundaries

Table 1. Comparison of Values of D by Geological Unit[a]

Geological Unit	This Study	*Carr* [1995]
Npl1	0.0454	0.0049
Npl2	0.0267	0.0012
Npld	0.0493	0.0111
Nplh	0.0127	0.0025
Nm	0.0016	0.0025
Hr	0.0041	0.0002
Hpl3	0.0052	0.0001
HNu	0.0062	0.0000
cs	0.0300	0.0008
cb	0.0164	0.0000
Aps	0.0159	0.0000
AHt	0.0596	0.0121

[a]In km^{-1}.

between geological units would deprive Hesperian terrain in the MC22 region of any VN within the resolution of our map.

3. Mapping Drainage Density

[9] Drainage density is usually defined as the total length of channels (valleys) per unit area. When the area is well defined, for example, a geological unit or a drainage basin, calculation of D is straightforward (see, for example, Table 1). However, such definition of D does not facilitate mapping variations of D within an individual unit or a basin. *Tucker et al.* [2001] proposed defining D in terms of a local and easily calculated variable, $L(x,y)$ - the downslope distance to the nearest channel (valley) from a given point (x,y). The mean value $\langle L \rangle$, calculated over a specified neighborhood of (x,y) is physically related to drainage density, $D(x,y) = 1 / (2 \langle L \rangle)$, at the point (x,y). A correlation length of $L(x,y)$, Λ, is used as the size of the neighborhood over which the $\langle L \rangle$ is calculated. Λ, read from the

covariance function of $L(x,y)$, is a distance beyond which L is not autocorrelated.

[10] We used the DEM of MC22 together with valleys obtained in Sec. 2 to calculate $L(x,y)$. Values of $D(x,y)$ are calculated using a circular neighborhood with a radius of $\Lambda = 150$ pixels. Figure 2 shows the map of $D(x,y)$ for the MC22 quadrangle, the blue-to-red gradient depicts values of $D(x,y)$ from its minimum of 0.0024 to its maximum of 0.113. The areas not covered by the color gradient are located either in closed depressions (mostly craters), or drain outside the MC22 region without encountering a valley, so no value of $D(x,y)$ can be calculated for them. Figure 2 indicates an omnipresent dissection of Noachian terrain. The only Noachian surfaces devoid of dissection are large craters, presumably superimposed on older terrain. However, spatial variations of D on regional (~ 1000 km) scale are observed; Terra Tyrrhenum is generally less dissected than Terra Cimmeria, and northern Terra Cimmeria is the most dissected. Significant variations of D on smaller (~ 100 km) scales are also present, but they are not correlated with either regional slope (calculated on the same scale as Λ), or elevation.

4. Discussion

[11] The MC22 quadrangle is roughly 1/3 Hesperian and 2/3 Noachian. Our detailed map (Figure 1) of VN in MC22 confirms the result of earlier, coarser global mapping in showing that valleys occur predominantly in Noachian terrain. However, whereas in the earlier map the isolated VN are scattered across Noachian terrain, in our map the VN are ubiquitous. We find no qualitative difference between degree of dissection among various Noachian geological units, spatial variations of D within the "dissected" Npld unit are equal to or larger than differences between average
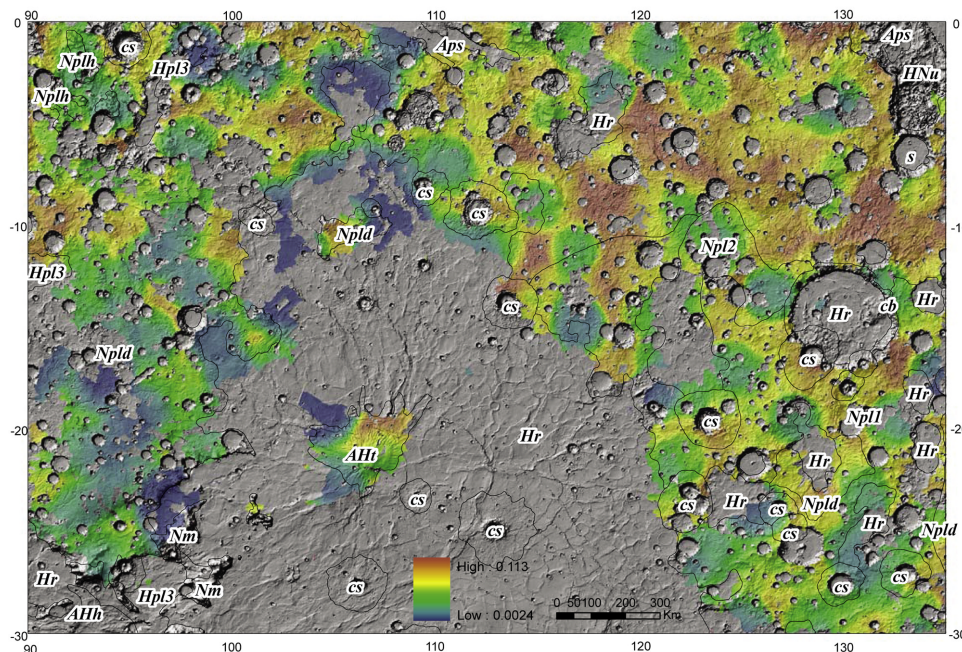
Figure 2. Map of $D(x,y)$ in the Mare Tyrrhenum quadrangle on Mars. The blue-to-red gradient corresponds to low-to-high values of $D(x,y)$, gray indicates areas for which $D(x,y)$ is undefined. Black lines indicate boundaries between geological units.

values of D for other mapped Noachian units (see Figure 2 and Table 1). Our findings suggests that dissection-based distinction between Npld and Npl1 units may be an artifact of an incomplete mapping; our more detailed mapping renders such distinction unnecessary. We find $D \approx 0.05$ km^{-1} to be an average value of drainage density in Noachian terrain (weighted by areas of geological units). This is an order of magnitude more than is implied by the Carr map and comparable to the values quoted by previous studies focused on localized sites; $0.065-0.095$ km^{-1} [*Hynek and Phillips*, 2003], $0.06-0.22$ km^{-1} [*Stepinski and Collier*, 2004], 0.53 km^{-1} [*Ansan and Mangold*, 2006]. Our results imply that relatively high values of D found at specific sites are representative for the entire Noachian terrain (at least within the MC22). At the same time, we find significant spatial variations of D on scale of ≥ 100 km, with many parts of northern Terra Cimmeria having $D \sim 0.1$ km^{-1}, whereas the southern parts of Terra Cimmeria and Terra Tyrrhenum having smaller values of D (see Figure 2). Interestingly, these variations do not correlate with terrain parameters; further studies are needed to find whether they are related to an original spatial variability in the degree of dissection, or to the spatial variations in subsequent terrain degradation.

[12] Ubiquitous presence of VN in Noachian makes the hypothesis of the groundwater sapping origin of VN unlikely notwithstanding their morphometric characteristics (see Sect. 1). Groundwater sapping requires a very specific combination of topographic and lithologic conditions, which are unlikely to be met everywhere in a region as large as the Noachian terrain within the MC22. Precipitation that leads to runoff erosion and, secondarily, to some sapping erosion, seems to be required to account for our result. However, the recent quantitative study [*Stepinski and Stepinski*, 2005] of drainage basins underlying individual VN indicate that they are morphologically different from typical terrestrial basins, their closest terrestrial analog being basins in the arid Atacama Desert. Thus, although omnipresent VN in Noachian point to somewhat warmer and wetter climate on early Mars, it was likely still a very dry and harsh environment by terrestrial standards.

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