Comparing Dissection Patterns of Mars and Earth: Paleoclimate Implications.

W. Luo and T. F. Stepinski, 1Department of Geography, Northern Illinois University, DeKalb, IL 60115, wluo@niu.edu, 2Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, tom@lpi.usra.edu.

Introduction: Martian valley networks (hereafter referred to as VN), discovered in 1971 by the Mariner 9 spacecraft, are geomorphic features on Mars exhibiting some visual resemblance to terrestrial river systems. The VN are present mostly in the Martian highlands and date to the Noachian. They point to a possibility that Noachian Mars was warmer and wetter than present-day Mars, perhaps capable of maintaining precipitation and some form of life. A geomorphic analysis of VN should, in principle, be able to establish a predominant style of erosion leading to their formation. Geomorphic features indicative of runoff erosion signals precipitation and a warmer climate whereas features indicative of erosion by groundwater sapping allow for cold and dry conditions during formation of VN. Alas, the geomorphic evidence is inconclusive and the origin of VN is still a topic of active research.

Some features, such as branching, dendritic patterns, origin near dividing ridges [1,2,3,4], consistency with crater degradation [5,6], and significant erosion requiring aquifer recharge [7,8,9], favor runoff erosion. Other features, such as widely spaced tributaries with alcove-like terminations [10,11], constant valley width downstream [12], short, stubby tributaries [13], flat longitudinal profiles [14], and U-shaped cross-sections, favor erosion by groundwater sapping. A common feature of all aforementioned studies is their reliance on detailed examination of individual valley systems.

Several hypothesis pertaining to the origin of VN were proposed in an attempt to reconcile the conflicting geomorphic evidence: episodic melting of snow accumulating during high obliquity epochs [15], high intensity rare storms (like in the Atacama desert, see [16]), and episodic, multi-year intense rainfall events due to basin-scale impacts or intense volcanic eruptions [17].

In order to test these hypothesis, a global analysis of dissection patterns must supplement the detailed local analysis of VN geomorphic features. This requires a global, sufficiently detailed map of VN. However, the only currently available global map of VN [18] is based on the Viking Orbiter images and contains only ~ 800 networks. The lack of more detailed global maps is due to the cost of their acquisitions by means of visual interpretation of images. Recent advances in machine extraction of valleys from topographic data [19] make it feasible to acquire global maps of VN by computer parsing of digital elevation models (DEMs) of planetary surface. In this paper we start to address the problem of VN origin from the global perspective by deriving the planet-wide map of dissection on Mars and comparing it to a similar map derived for the Earth. We use global-scale, similar resolution DEMs of Earth and Mars to extract valleys over the entire planetary surfaces. These data sets are used to derive maps of dissection density and their zonal statistics.

Data sources: The DEM data for Mars comes from the Mars Orbiter Laser Altimeter (MOLA) Mission Experiment Gridded Data Records (MEGDR) [20]. The MEGDR DEM has a spatial resolution of 1/128 degrees/pixel or about 463 m/pixel at the equator. Note that MEGDR is an interpolated DEM, as an across-the-track spacing of the original MOLA measurements is ~ 1000 m at the equator [21] so some of the grid cells lack direct measurement values. This notwithstanding, the MEGDR is suitable for our study, as we are only interested in deriving large-scale properties of Martian dissection for the purpose of statistical analysis. Only the portion of the MEGDR located between 50° N and 70° S latitudes is used because our focus is on the Noachian terrain.

For the Earth we use the Global Land One-km Base Elevation (GLOBE) 30-sec/pixel (~ 1 km/pixel at the equator) DEM developed by the National Geophysical Data Center (NGDS, 2008), which is the best available 30-arc-second global digital elevation data set, compiled from various sources.

Methods: Automated delineation of valleys and/or streams from a DEM is a rather standard task in terrestrial hydrology. The established methods follow the flow along local directions of the steepest descent (i.e., they are based on the idea that water flows downhill). Streams extracted by the steepest descent method tend to be spatially uniform; the method is not capable of mapping spatial variations of dissection [22,23] and it should not be used to map surfaces where non-uniform dissection pattern is observed and/or expected. This includes the Noachian terrain on Mars because VN lack spatial integrity; dissected areas are commonly separated from each other by undissected areas of similar or bigger size. Even on Earth, where dissection tends to be uniform on small spatial scales, the steepest descent method should not be used for assessing the
density of dissection on spatial scales on which its non-uniformity becomes evident [23].

In this work we use a terrain morphology-based extraction method [19] that identifies concave upward (U-shape) topographic features as valleys. The concave upward features are associated with the cells in a DEM having positive curvature. This method has been previously applied to extract VN in the entire MC22 [24] and MC19 [25] quadrangles, yielding maps of VN that are much more detailed than the Carr map. The method was also applied to a large site in the Cascade Range, Oregon, USA [23], demonstrating its ability to identify non-uniform dissection in the terrestrial context. For the present study we have applied the morphology-based extraction technique to the MEGDR and GLOBE grids. Masks were applied to the resulting data sets of valleys to filter out ocean floor on Earth and non-Noachian terrain on Mars. A maps of dissection density, DD, is calculated by applying a circular moving window to the corresponding map of valleys. A given cell is assigned a value of DD corresponding to a ratio of the total length of valleys in the window to the area of the window. The results presented here were obtained using a window with a radius of 100 km, but the results are not overly sensitive to the size of the window.

Results: Figure 1 shows the maps of DD for Earth and Mars. As expected the values for Mars (0-0.12 km$^{-1}$) are lower than for the Earth (0-0.32 km$^{-1}$), but the ranges are in the same order of magnitude. The derived values of DD for Earth are considerably smaller than ~1-100 km$^{-1}$ quoted in literature [26]. This is because of relatively coarse resolution of the DEM. Nevertheless, the comparison of DD patterns on the two planets is fair because DEMs of similar resolution are used. The maps on Figure 1 reveal striking differences in spatial distributions of high DD regions on the two planets. In order to quantify these differences we have calculated zonal statistics of DD with respect to elevation, latitude, and regional (33 km$^{-1}$) slope. The result of the zonal statistics calculation is a function showing a dependence of DD (averaged over the entire zone) on a variable of interest. Figure 2 shows the comparison of zonal statistics, the top row corresponds to Earth whereas the bottom row corresponds to Noachian Mars.

On Earth, the highest values of DD are found in geographically disparate locations that, however, are all characterized by high elevations and steep slopes. Within such locations the DD is uniformly high. Could we infer the mechanism of valley formation on Earth having only the topography data and the global map of DD at our disposal? We could definitively eliminate groundwater sapping as a viable mechanism, but getting the right answer would be challenging without additional data. As it happens, high values of DD on Earth are found in the orogenic belts where high topographic relief (caused by the orogenic uplift) combined with the rainfall-fed runoff erosion give rise to the high values of DD. Thus, the pattern of high DD regions on Earth is explained by combination of an erosional style (runoff) with a separate physical phenomenon (tectonics).

On Mars, the distribution of DD is directly opposite of what is found on Earth - rather homogeneous on large spatial scale, but very inhomogeneous on smaller scales. As indicated by latitudinal zonal statistics, the average values of DD are highest in the equatorial regions, north of ~30°S, and decrease rapidly south of ~30°S latitude. Although the mean values of DD are relatively high throughout the equatorial belt, there is a strong local variability. This reflects the well-known lack of spatial integration of VN. No systematic variation of an average value of DD with elevation is observed on Mars. On the other hand, a systematic decrease of the value of DD with slope is detected. We have also calculated a relationship between zonal mean of DD and the crater density on Mars. The crater density was derived from the Catalog of Large Martian Impact Craters [27] using a circular moving window of radius 150 km. A given cell is assigned a value of crater density corresponding to a ratio of the total count of craters in a window to the area of the window. Figure 3(left) shows the results; on average the value of DD increases with the crater density. In other words, the spatial distribution of craters and VN are positively correlated.

Discussion. The aforementioned features of the global distribution of DD on Mars impose constrains on possible scenarios of VN formation. The strong local variability of DD argues against global-scale and persistent precipitation, but the planet-wide extent of the region where average values of DD are high requires some sort of a global-scale mechanism. That mechanism cannot depend on elevation, but may be weakly dependent on regional slope. It must be correlated with the process of impact cratering.

We submit that a VN formation mechanism best satisfying the restrictions imposed by the global distribution of DD is the impact cratering itself. In this scenario, as originally proposed by [17] and later elaborated by [28] and [29], impactors as small as 10 km in diameter result in a global warming for 10-20 seasons and precipitation of 0.2 m total liquid water (TLW). Larger impacts results in longer periods of warming and more precipitation. In addition, impact-induced
hydrothermal activity [30] can force local groundwater sapping. Because impacts were ubiquitous in Noachian, dissection density due to VN carved by impact-induced erosion should be homogenous on large-scale but variable on spatial scale of the order of the largest craters. This is in agreement with the map of DD shown on Fig. 1. The only constrain not fulfilled by the impact-induced erosion is the relative lack of valleys (low values of DD) southward of ~30° S. This seems incompatible with ubiquity of impacts.

We propose that observed deficiency of valleys southward of ~30° S is not a primordial feature but rather the effect of subsequent surface modification. Indeed, the terrain located southward of ~30-40° S is known for its “softened” appearance. This attribute of mid-to-high altitude terrain has received most attention in connection with craters [31,32] but it affects all surface features. It is related either to the viscous relaxation due to presence of ground ice [33] or to mantling [34]. We propose that originally VN were distributed uniformly over the Noachian, but those located southward of ~30-40° S were softened beyond recognition resulting in a presently observed distribution as encapsulated by the map of DD shown on Fig. 1.

To further test this hypothesis, we extracted valley depth information from the topographic data for both planets by using average of the cells surrounding valley cells to approximate their pre-incision elevation and calculating the difference between this pre-incision elevation estimate and the current elevation. The latitudinal zonal statistics of the depth estimates are shown in Figure 3(middle and right). For Earth, there is great variability in the depth with latitude but no systematic trend, indicating latitude independent tectonic activities. For Mars, the depth does decrease with increasing latitude, consistent with the scenario that VN were created by episodic and short-lived precipitation events and groundwater sapping activities induced by impact cratering and thus initially uniformly distributed over Noachian, but later relaxed at higher latitude regions, making the valley depth shallower there.

Conclusion: Global maps of dissection can now be constructed by means of computer parsing of digital elevation models. This new technique offers an opportunity to test hypothesis of VN formation from a global perspective, a welcome addition to the tests based on local geomorphic features. Dissection patterns on Earth and Mars are completely dissimilar. Terrestrial case reveals that climatic data by itself is not sufficient for a correct interpretation of dissection pattern. Dissection pattern on Mars points to the impact cratering as an ultimate source of VN. The impacts cause a series of alterations to an otherwise cold and dry global climate. These climatic diversions create episodic and short-lived precipitation events and groundwater sapping activities that are responsible for the patchy character of VN. They also explain mixed and inconclusive geomorphic evidence and observed lack of maturity [35] in the development of VN. We call upon terrain softening to explain paucity of VN in the mid-to-high southern latitudes.

Acknowledgements. We acknowledge support by NASA (WL under grant NNX08AM98G, TFS under grant NNG05GM316). A portion of this research was conducted at the Lunar and Planetary Institute under contract CAN-NCC5-679 with NASA. This is LPI Contribution No. 1436.

Figure 1: Global maps of dissection density (DD) on Earth (left) and Mars (right). Blue-to-red gradient corresponds to low-to-high values of DD. The same colors on the two maps do not correspond to the same values of DD. The gray areas on Mars correspond to the regions that are not classified as Noachian, or to the regions for which DD is not defined.

Figure 2: Zonal statistics of dissection density (DD, km⁻¹) based on elevation (left), latitude (middle), and regional slope (right).

Figure 3: Zonal statistics of dissection density (DD, km⁻¹) based on crater density (left) and zonal statistics of valley depths based on latitude for Earth (middle) and Mars (right).