Orientation of valley networks on Mars: The role of impact cratering

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Received 1 October 2012; revised 13 November 2012; accepted 14 November 2012; published 21 December 2012.

[1] We compare, on a global scale, the degree of correlation between orientation of stream networks and topographic aspect on Mars and Earth. The orientation of streams on Earth is a reflection of local, underlying geology but, in general, it correlates with regional topographic aspect. However, the orientation of valley networks, prominent features on Mars, thought to be fossils of ancient streams, are shown not to be correlated with topographic aspect. Instead, we show that orientations of valley networks are highly dispersed with only a very weak preference to the regional topographic aspect. We attribute this dispersion to significant altering of topography by impact cratering which is not matched by sufficiently efficient runoff erosion. Such explanation is supported by the fact that local regions on Mars with relatively low crater density display a level of correlation between valley orientation and aspect comparable to that calculated for terrestrial surfaces. In addition, the cratering explanation is further supported by means of landscape evolution simulations. Our finding provide an additional support to the idea that climate on early Mars, although wetter than its present climate and capable of producing rainfall, was nevertheless too arid to enforce (through erosion) correlation between stream orientations and topographic aspect. **Citation:** Luo, W., and T. F. Stepinski (2012), Orientation of valley networks on Mars: The role of impact cratering, *Geophys. Res. Lett.*, *39*, L24201, doi:10.1029/2012GL054087.

1. Introduction

[2] Martian Valley networks (VNs) and associated alluvial deposits offer the best evidence for past water cycles on Mars [*Craddock and Howard*, 2002; *Fassett and Head*, 2008]. Since the first discovery of VN, the planetary literature has alternately emphasized the similarities and differences between terrestrial streams and Martian valley networks [*Masursky*, 1973; *Pieri*, 1980; *Carr and Chuang*, 1997; *Mangold et al.*, 2004] and both sets of observations are valid and relevant to the paleoclimate of Mars [*Irwin et al.*, 2011]. Although recent global mapping efforts [*Luo and Stepinski*, 2009; *Hynek et al.*, 2010] found more VNs than have been previously mapped [*Carr and Chuang*, 1997], they are still typically less integrated and less mature than terrestrial streams [*Irwin et al.*, 2011], suggesting an overall arid climate condition (compared to terrestrial one) and/or intermittent, rather than continuous, fluvial conditions [*Irwin et al.*, 2008].

[3] Previous analyses of topography and gravity data suggest that the long wavelength features such as Tharsis-induced trough and antipodal high were largely in place by the end of the Noachian Epoch and they exerted control on the location and general orientation of valley networks as measured at the downstream ends of valley network trunks [*Phillips et al.*, 2001]. Thus it may be expected that the distribution of VN orientations should follow distribution of slopes on the Noachian terrain. In this paper we examine the orientation of valley networks on Mars in relation to slope orientation (or topographic aspect). Our recent detailed global mapping of VNs [*Luo and Stepinski*, 2009] provides detailed data for re-examination of VN orientation in relation to slope orientation. Our analysis shows that, contrary to what may be expected, the distribution of VN orientations does not follow the distribution of topographic aspect. Instead, we have found that whereas distribution of topographic aspect is strongly peaked toward the north (reflecting the overall dichotomy of Martian surface), distribution of VN orientations is much broader, with all northerly directions well represented. This is in contrast to terrestrial landmass surface where the two distributions (topographic aspect and orientation of valleys) are highly correlated. We attribute observed strong dispersion of VN orientations to significant alteration of Martian overall topography by impact cratering. In order to support this assertion we calculate distributions of aspect and VN orientation restricted to (Noachian) regions on Mars with varying degrees of crater density and demonstrate that correlation between the two distributions depends on crater density. In addition, we show that computer simulation of fluvial erosion on a cratered slope generates similar dispersion of valleys orientation with respect to topographic aspect.

2. Data Source

[4] The topography data for Mars was obtained from Mars Orbiter Laser Altimeter (MOLA) Mission Experiment Gridded Data Records (MEGDR) [*Smith et al.*, 2003] and the VN data was derived from a morphology based algorithm aided with manual editing against THEMIS mosaic [*Christiansen*, 2004] to remove false positives [*Luo and Stepinski*, 2009]. To compare results calculated for Martian surface with those calculated for terrestrial surface we have selected the continent of South America. The topography data for South America was obtained from the Global Land One-kilometer Base Elevation (GLOBE) digital elevation data set (http://www.ngdc.noaa.gov/mgg/fliers/globedem.html) and the

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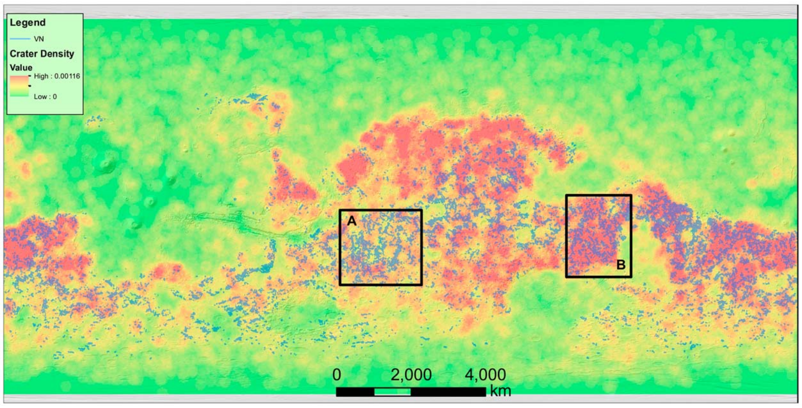

Figure 1. Map of Mars showing spatial distribution of valley networks (VNs) in the Noachian terrain. Box A indicates area with relatively low crater density and box B indicates area with high crater density. Background shows crater density calculated from Barlow crater dataset (see text for details).

stream data for South America was obtained from USGS hydroSHEDS data (http://hydrosheds.cr.usgs.gov/).

3. Data Processing and Results

[5] VNs used in our study are extracted using computer algorithm of *Luo and Stepinski* [2009]. Ideally, a VN has a spanning binary tree geometry with an outlet being at the root of the tree. The tree branches at the nodes, and the sources are the points farthest upstream. The links are the segments of channels between two successive nodes, or a node and a source, or a node and the outlet. The branching hierarchy of a network is described by the Horton-Strahler stream ordering (see *Rodriguez-Iturbe and Rinaldo* [1997] for details). We have calculated orientation of each link in the VN separately (using ArcGIS's Linear Directional Mean tool) as oppose to calculating the orientation of the entire network consisting of a tree of links as the latter can sometimes give misleading or even erroneous result. The orientation of the entire network (defined as the orientation of a vector connecting outlet with the farthest point located at the main stream) depends strongly on a particular shape of the drainage basin and thus is not best suited for comparison with regional topographic aspect. The orientation of each link was calculated as its downstream azimuth. Orientations were calculated for a subset of VN dataset [*Luo and Stepinski*, 2009] fulfilling the following conditions: (a) link length is greater than 5 km, and (b) link is located on Noachian terrain. Our dataset contains 41,537 such links dissecting the area of 7×10^7 km^2. The average upstream contribution area of these links is about 290 km^2 and the average length is about 15 km. For South America data, we selected a subset of major streams with the lower limit (300 km^2) on their upstream contribution area comparable to that selected for Mars. Such selection resulted in 37,738 stream links dissecting the area of 2×10^7 km^2. The average length of these stream links is about 7 km. Our selection criteria ensures the general comparability between the Martian VN and the terrestrial streams notwithstanding higher dissection density of terrestrial surface.

[6] Distribution of topographic aspect depends on baseline length used to calculate a slope. Ideally, the baseline should be equal to the size of the network and thus it should vary from location to location. For simplicity, we calculated aspect on the basis of constant baseline equal to 50 km. We re-sampled both, Martian and terrestrial, DEMs to the resolution of 50 km/cell and use this coarser DEMs to calculate topographic aspect as the azimuthal direction of steepest descent. We have tried different base-line lengths and found that the distribution of aspects calculated this way to be relatively stable to changes (within the same order of magnitude) in the baseline length.

[7] Figure 1 shows the spatial distribution of VNs selected for our study and Figure 2 shows distributions of aspects and valley orientations for Noachian Mars and South America. It is clear that on Noachian Mars dominant topographic aspect is toward N, NNW, and NNE, but the distribution of VN

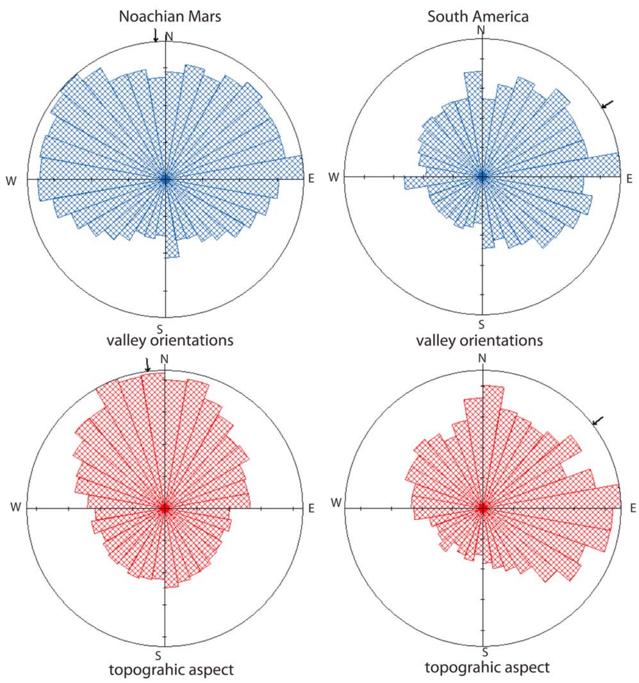

Figure 2. Comparison of distributions of VN orientation and topographic aspect on Noachian Mars (left) and South America (right). Distributions are shown as rose diagrams, blue indicates VN orientation and red indicates topographic aspect. Arrows indicate average direction. (Rose diagrams created with GEOrient software.)

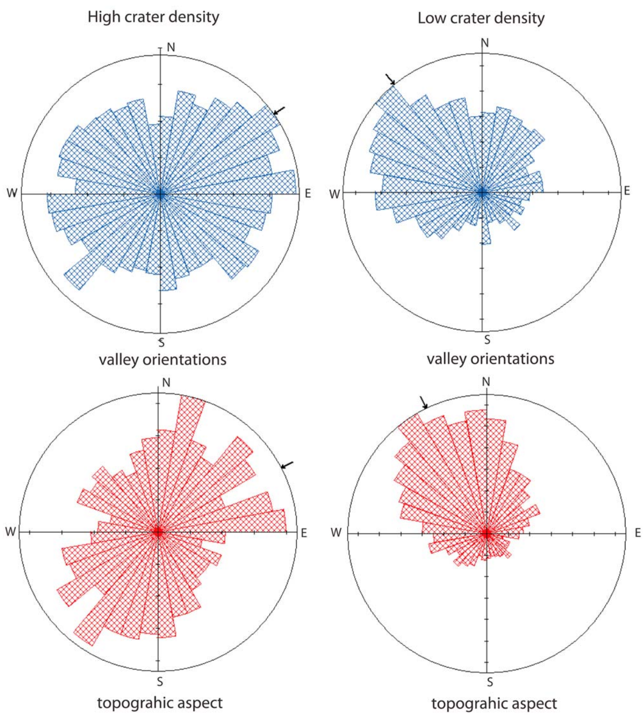

Figure 3. Comparison of distributions of VN orientation and topographic aspect in the region of high crater density (left) and low crater density (right) on Noachian Mars (see Figure 1 for their locations). Distributions are shown as rose diagrams, blue indicates VN orientation and red indicates topographic aspect. Arrows indicate average direction.

orientation is NW, NW, E, W. There is no significant correlation between the frequency of VN orientations and frequency of topographic aspects ($R^2 = 0.17$). Recall that perfect correlation is $R^2 = 1$ and no correlation is $R^2 = 0$. This result is contrary to what was previously reported [*Phillips et al.*, 2001]. Note however that their analysis pertained to a larger spatial scale and was based on less detailed map of VNs. On the other hand, distributions of stream (and thus valley) orientation and topographic aspect in South America are generally in concordance with each other both visually and through the correlation value ($R^2 = 0.76$).

[8] We also have examined distributions of VN orientation by Strahler stream order. For Mars, the distribution of first order streams is peaked in SSE and SSW, very different from the distribution of aspects. This is probably because first order stream are generally shorter than 50 km - the value used as a baseline in our calculation of topographic aspect. Distributions of VN orientation for higher order streams indicate northerly preference but with significant scatter. For South America, despite some scatter, distribution for all stream orders peaks to the east in concordance with the distribution of topographic aspect.

[9] These results point to a different character of Martian and terrestrial surfaces; whereas terrestrial topography and character of drainage are in concordance with each other, this is not the case on Mars. The alignment of topographic aspect and stream orientations on Earth can be attributed to importance of fluvial erosion in shaping terrestrial topography. By the same token, lack of such alignment on Mars can be interpreted as stemming from decreased importance of fluvial erosion for the large scale topography of Mars. In particular, scattered orientations of VNs can be attributed to impact cratering which, in the absence of abundant fluvial erosion, alters the topography from the prevailing dominant regional slope and forces VN orientations to adhere to these terrain modifications.

[10] In order to confirm this reasoning, we compared two areas on Noachian Mars, one with relatively (for Noachian surface) low crater density and one with high crater density. These two areas are indicated in Figure 1 as A and B, respectively. The crater density map was generated from Barlow crater database [*Barlow*, 1988] using a circular moving window with radius of 150 km. Figure 3 shows the distributions of VN orientations and topographic aspects for the two areas. For the high crater density area (box B in Figure 1) the results are similar to those for the entire Noachian Mars - there is no concordance between distributions of VN orientations and aspects; indeed the correlation coefficient between the two is $R^2 = 0.02$. However, for an area with relatively low crater density (box A in Figure 1) there is a general concordance between distributions of VN orientations and aspects; the correlation between the two variables is $R^2 = 0.60$, almost approaching the correlation value for the South America.

4. Computer Modeling

[11] To further test our finding, we used a computer model to simulate evolution of a gently tilted surface subject to: (a) fluvial erosion alone, (b) impact cratering followed by fluvial erosion. We compared the topographic aspects and the orientation of resulted stream links in surfaces resulting from the two computer runs. For our calculations we used the Mars Surface Landform Model (MSLM), which simulates long-term landform evolution by weathering, mass wasting, fluvial, eolian, groundwater, and lacustrine processes and has been used extensively to understand landform evolution on Mars [*Howard*, 1994, 1997, 2007; *Forsberg-Taylor et al.*, 2004; *Luo and Howard*, 2008; *Barnhart et al.*, 2009]. MSLM is an updated and gravity-scaled version of the terrestrially based Detachment Limited Model (DELIM), which has successfully predicted the evolution of terrestrial landscapes [*Howard*, 1997]. The model setup for our calculations is similar to that in *Luo and Howard* [2008] with a grid size of 256 by 256 and cell dimension equaling to 400 m by 400 m. The entire simulation domain has dimension of about 102 km by 102 km. Each process scenario was run for 2500 iterations, which roughly correspond to a minimum of 2.5 million years on the basis of terrestrial process rate scaling in arid to semiarid climates. Under scenario (a), the gently tilted plane with some random micro-scale roughness was subject to rainfall runoff erosion; the resultant terrain and stream network are shown in Figure 4 (left). Resultant stream orientation and topographic aspect are generally in concordance with each other both visually (Figure 4, left) and through correlation value ($R^2 = 0.79$). However, under scenario (b) (see Figure 4, right), where the same gently tilted plane was first subject to impact cratering and then by rainfall runoff erosion, the resultant stream orientations are much more dispersed than the topographic aspects of the cratered surface (Figure 4, right) and the correlation is low ($R^2 = 0.22$). It should be noted that this study did not consider the role of new craters disrupting forming fluvial networks, but the simple case of fluvial network formation on a pre-existing

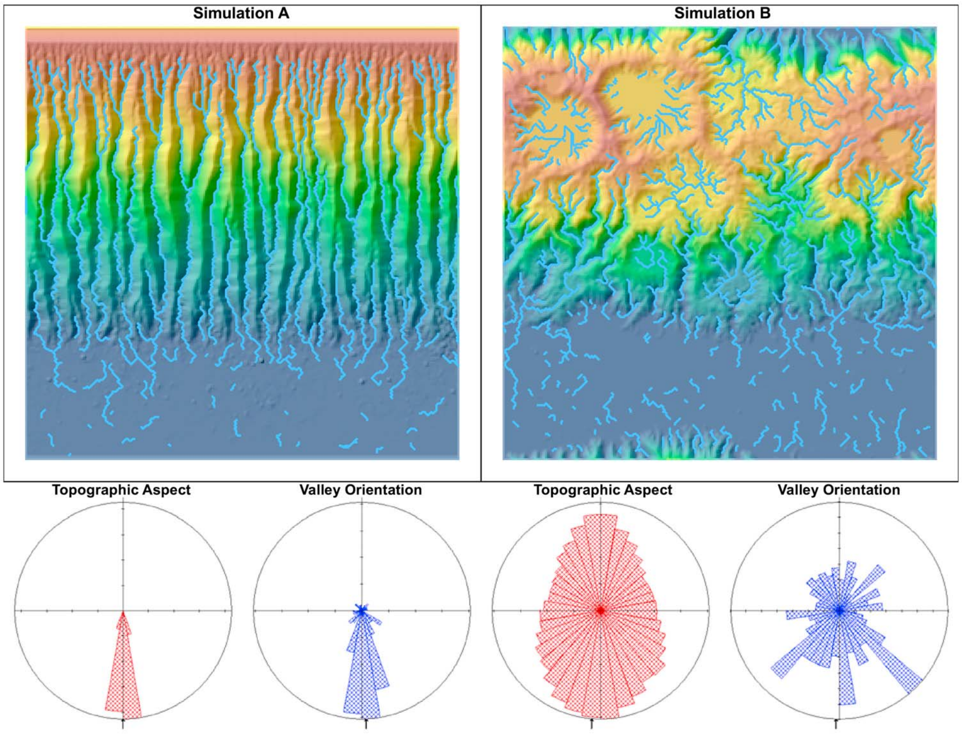

Figure 4. Results of landscape evolution models. Scenario A: Landscape evolved due to rainfall runoff erosion of a gently tilted surface (slope = 0.01 degree) with some initial random micro-scale roughness. Scenario B: Landscape evolved from a gently tilted surface due to impact cratering followed by 2.5 millions years of rainfall runoff erosion. Rose diagrams of topographic aspect and valley orientations are shown for each scenario.

crater-formed topography (basins and rims) superposed on a regional slope. However, this simple case is sufficient to illustrate the role of impact cratering in altering local topography and changing VN orientations.

5. Discussion and Summary

[12] Our analysis has revealed yet another difference between the VNs on Mars and terrestrial stream networks. We have shown that whereas orientations of terrestrial streams are strongly correlated with topographic aspect, no similar correlation holds between orientation of VNs and topographic aspect of Noachian Martian terrain.

[13] We have demonstrated that impact cratering, coupled with absence of erosion on relatively fast geological time scale, capable of destroying the local-to-regional relief of the impact basins and their rims, provides the best explanation for the decoupling of VN orientations from topographic aspect. The role of impact cratering in explaining the character of VNs has been previously noted [*Craddock and Howard*, 2002; *Irwin et al.*, 2011; *Barnhart et al.*, 2011]; these authors commented that impact events could have frustrated valley network development and led to the current immature appearance of the VNs. Our analysis corroborates this point of view, but extents it to a global scale with firm statistics. Fluvial activity occurred during late heavy bombardment, so that the fluvial networks were being disrupted by cratering. Thus the overall amount of fluvial erosion might have been much greater than is evident from the fossil drainage networks, because much earlier fluvial dissection was destroyed by later impacts. Not only the appearance of any single valley network is significantly influenced by cratering, but the combination of impacts and lack of sufficient erosion of craters by runoff results in overall decoupling of VN orientations from the topographic aspect. This finding corroborates the notion that early Martian climate was arid even if it supported rainfall and stable water on its surface.

[14] **Acknowledgments.** This work was supported by NASA under grant NNX08AM98G. We would like to thank the two anonymous reviewers for the helpful reviews, which improved the quality of this paper.

[15] The Editor thanks the two anonymous reviewers for their assistance in evaluating this paper.

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