UTILIZING VALLEY NETWORK JUNCTION ANGLE TO ESTIMATE THE DURATION OF "WARM" MARS. Xuezhi Cang[1] and Wei Luo[2], [1] Northern Illinois University (xcang@niu.edu) [2] Northern Illinois University (wluo@niu.edu)

Introduction: Although the widespread dendritic valley networks (VNs) on Mars strongly suggest erosion by overland flow of water from precipitation, the climate models of Mars failed to reproduce the "warm" Mars scenario due to the faint young Sun. Scientists are still debating whether episodic warm or non-precipitation dominated erosion can create the observed VNs. Despite the ongoing debate, the supporters of "Warm" Mars and "Cold" Mars seem to agree that abundant liquid water flowed on Mars in the Noachian period [1,2].

Previous research suggested that the means of stream junction angles on Earth varied with different climatic conditions [3]. The frequency distribution of junction angles, which includes more information than mean value alone and is less influenced by the resurfacing processes, can be accurately extracted from the existing stream datasets. Thus the frequency of VN junction angles offers a new way for understanding the early Mars climatic conditions. One comparison between the junction angles of terrestrial streams and those of Martian VNs concluded that the VNs on Mars were formed primarily by precipitation-sourced overland flow erosion and not in permafrost environment [4]. However, this research did not investigate the possibility of the "cold but episodic warm" Mars, because the "warm" scenario could exist but lasted very shortly.

The key to addressing this problem is the formation timescale of VNs (or the duration of water flow in VNs). The longer the water flow duration, the higher the probability of a "warm" Mars. To further investigate the early climate of Mars, we first established the association between the frequency distribution of stream junction angles and the climatic conditions on Earth and applied that relationship to estimate the Noachian climatic condition on Mars based on VN junction angles, we then assessed the duration of "warm" Mars.

Data and Method: The terrestrial stream junction angles were extracted based on NHDPlusV2 Dataset of the conterminous U.S. The climatic factors were represented by aridity index (*AI*) and Mean Annual Precipitation (*MAP*) provided by CGIAR-CSI [5]. (*AI* = *MAP*/*MAE*, where *MAE* is Mean Annual Potential Evapotranspiration [5].) We utilized the averaged *AI* and *MAP* by HUC-6 (Hydrologic Unit Code-6) watershed as the dependent variables, the frequencies of junction angles in bins of 10° as the independent variables, i.e., we have 18 independent variables for each averaged climatic variable within each watershed. Then, we ran multiple linear regression to establish the association between climate and junction angle. The *RMSE* of regression between Log10(*AI*) and frequencies of junction angles is 0.16, and the *RMSE* of regression between Log10(*MAP*) and frequencies of junction angles is 0.17.

The Martian VN junction angles were extracted from the VN dataset by Luo and Stepinski [6]. The entire Mars surface were divided into small tiles or grids, each with size of 500 km by 500 km, which can be considered a climatically homogenous area. We selected the grids within denser junction angle belt for analysis. Before we apply and scale the association between junction angle and *AI* established on Earth to estimate the *AI* of Mars, we need to consider the different radiation each planet receives from the Sun.

The Potential Evapotranspiration (*PET*) on Earth can be related to radiation by Hargreaves evapotranspiration equation [7] as follows:

$$PET = 0.0023*RA*(T_{mean} + 17.8)*TD^{0.5} \text{ mm/month} \quad (1)$$

where T_{mean} is mean temperature; *TD* represents daily temperature range; and *RA* is extra-terrestrial radiation.

Due to the faint young Sun and distance between Mars and Sun, Mars can only get 1/3 of solar radiation that Earth receives. The mean temperature and daily range have more uncertainty. At the lower end, we assume T_{mean} = 0°C and *TD* = 22.2°C (same as terrestrial value), which will make Mars *PET* about 1/5 of terrestrial value. At the upper end, we assume T_{mean} = 9.75°C [8] and *TD* = 60°C (based on Viking record, [9]), which would give Martian *PET* about 1/2 of terrestrial value. We assume these same ratios in *PET* estimates also apply to *MAP* estimates when *AI*s are the same.

Next, we divide the minimum cumulative volume of water required to form the VNs [10] by the discharge (assuming that 1/3 to 1/2 of *MAP* runs off) to obtain the VN formation timescale. To estimate the length of the "warm" Mars, we also adopted a 1% intermittence which assumed that Mars' climatic condition was semi-arid or arid [11].

Results: To compare Mars' frequency distribution with that of Earth, we classified the watersheds of contiguous U.S. to five categories based on their *AI*. The mean *AI* of arid area is 0.27 and the mean *AI* of semi-arid is 0.49. The estimated *AI* on Mar based on global frequency distribution is 0.45, between the values of terrestrial arid and semiarid areas. However, based on the frequency distributions shown in Figure 1, *AI* on Mars is closer to that of the arid area of conterminous U.S..

Figure 2 shows the spatial distribution of estimated *AI* of Mars based on the terrestrial regression and the scaling discussed earlier. To avoid the complication that downstream areas receive water from precipitation and contribution from upstream and the fact VNs at lower elevation are more likely

influenced by non-fluvial processes, we separately considered upstream grids (shown as hatched areas).

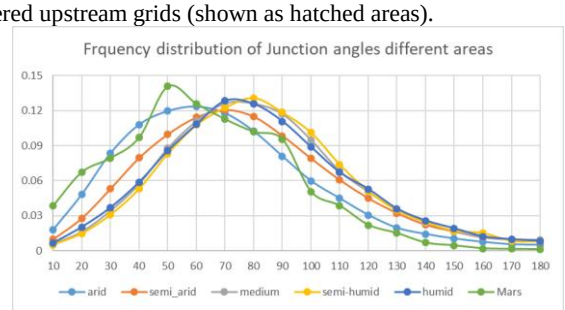

Figure 1. Frequency distribution of junction angle of Mars and of U.S. divided by *AI*

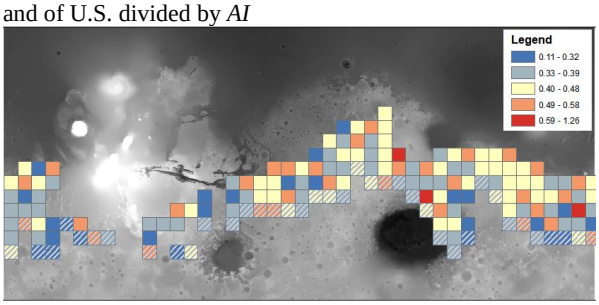

Figure 2. Spatial distribution of estimated *AI*s of Mars.

The calculated timescales are shown in the Table 1. The upper limits were obtained by using the lower end of scaling ratio (1/5) and assuming 1/3 of precipitation runs off. The lower limits were based on upper end of the scaling ratio (1/2) and assuming 1/2 of precipitation runs off.

Table 1. Estimated formation timescale of VNs

	Lower limits (million years)	Upper limits (million years)
VNs in upstream grid	4.87	20.31
Global VNs	11.36	47.29

The correlations between estimated climatic factors and latitude and between climate factors and minimum water volume required to form the VNs [10] are shown in Table 2 based on Spearman's rank correlation. To make interpretation easier, the values of latitude from north pole to south pole is defined as 0~-180°.

Table 2. Correlation between estimated climatic factors and locations

	AI	*MAP*
Latitude (0 N pole~-180°S Pole)	-0.279*** $p < 0.0002$	-0.191* $p = 0.013$
Minimum water volume required to form VNs	0.195** $p = 0.0011$	0.160* $p = 0.039$

Discussion and conclusion: On the global scale, the estimated *AI* of early Mars based on frequency distribution of junction angles was between the arid and semi-arid areas (and closer to arid, Fig. 1). This result is consistent with the previous Mars junction angle research [4]. The mean of the global estimated *AI* (0.45) is also within the equivalent range of X-ratios, which is related with the ratio between *MAE* and *MAP* [12,13].

The spatial distribution of *AI* showed that the grids near dichotomy boundary were generally wetter than those farther away in the southern highland (See also Table 2). The trend supports the hypothesis that the Mars had a global hydrological cycle and the surface water flowed from southern highland to the northern basin globally, which means Mars had a "warm" climate when the VNs were forming. The estimated *AI* and *MAP* have positive correlation with the spatial distribution of minimum water volume required for form VNs [10], consistent with wetter area supplying more water for erosion processes.

Our estimated duration of "warm" period using all VNs (with an upper limit of around 50 million years) is longer than the duration using upstream areas only (4-20 million years). Because VNs at lower elevation are more likely to be influenced by non-fluvial processes, we prefer the estimate of duration using upstream grids (4-20 million years). It is important to note that our estimated length of "warm" period was obtained by integrating the climatic model and the geomorphological evidence.

Using different landform characteristics and models, Orofino et al., [11] also estimated the length of "warm" period, with results consistent with ours, although ours have a narrower range. Considering the Noachian period is 400 million years, both results support the hypothesis that Mars was "episodically warm".

References: [1] Ramirez and Craddock (2018) Nature Geoscience, 11. [2] Wordsworth et al., (2018) Nature Geoscience, 11. [3] Seybold et al., (2017) GRL,44. [4] Seybold et al., (2018) Science advances,4. [5] Zomer et al., (2008) AGR ECOSYST ENVIRON,126. [6] Luo and Stepinski (2009) JGR,114. [7] Hargreaves and Allen (2003) J IRRIG DRAIN E-ASCE, 129. [8] Wordsworth et al., (2015) JGR, 120. [9] Lewis et al., (1999) JGR, 104. [10] Luo et al., (2017) Nature communications, 9. [11] Orofino et al., (2018) Planetary and space science. [12] Matsubara et al., (2011) JGR,116 [13] Matsubara et al.,(2013) JGR,118.