ROAMING ZONES OF PRECIPITATION ON ANCIENT MARS AS RECORDED IN VALLEY NETWORKS.

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Introduction: The presence of valley networks across much of the ancient surface of Mars is the most significant indicator that the martian surface environment was once capable of sustaining long-lived flowing water under drastically different atmospheric conditions. Most, though not all, of the martian valley networks are located on ancient surfaces, and appear to have formed during a final stage of fluvial erosion that occurred sometime during the Late Noachian (~3.7 to 3.82 Ga) or Early Hesperian (~3.7-3.6 Ga) [e.g. 1-4]. The formation of large drainage networks, alluvial fans, and deltas during this period indicates sustained flows of water [5], suggesting the early martian atmosphere during which most of the valley networks formed was either continuously or episodically warmer, thicker, and wetter than today.

Using coregistered THEMIS daytime IR and MOLA gridded topography in ArcGIS® we measured the drainage density and determined the crater size-frequency distribution of martian valley networks to better characterize the timing and variability of valley network formation during the Late Noachian.

Morphology: All of the valley networks studied here demonstrate characteristics consistent with formation primarily by precipitation; including densely spaced dendritic form with interiors that increase in width and depth downstream, meandering main trunks and major tributaries that occasionally also exhibit multiple interior channels, braiding, and terracing, and tributaries that often reach right up to drainage divides. The major tributaries or main trunk of some valley networks have morphologies that indicate they have experienced late-stage reactivation consistent with erosion from a very localized source of water, such as from a paleolake [6,7] or groundwater sapping [8,9]. Both pristine and degraded preservation states are seen in the valley networks. Often both U- and V-shaped interiors are observed within a single valley network system. All of the valley networks in this study that have degraded channels exhibit both U- and V-shaped interiors while the more pristine channels either had primarily V-shaped interiors or had both U- and V-shapes. These observations support the hypothesis that interior shape may be more an indication of the preservation state of the valley than of its formation mechanism.

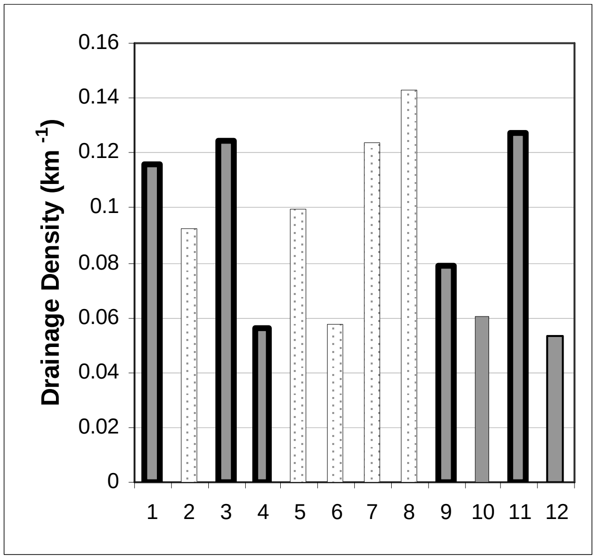
Drainage Density: Drainage density is the ratio of total stream length within a network to the area of the drainage basin and essentially reflects the average spacing of the channels within the drainage basin. Determination of drainage density is greatly affected by the ability to identify the small, shallow tributaries. For Mars, this depends on the resolution and coverage of the data used to map the valley networks as well as the preservation of these small, shallow tributaries from infilling [e.g. 2].

To define the drainage area in this research, a convex hull method was used in which the visible exterior tributaries were connected with straight lines to form a polygon in which none of the internal angles exceeded 180°. A convex hull was used instead of drainage divides for determining the drainage area because impacts and geologic processes subsequent to the end of valley network formation likely severed valley segments and/or altered the location of drainage divides over the last ~3.5 billion years [10]. Furthermore, the surface of Mars has experienced sufficient modification over this time to cause possible erasure of the shallower valley segments, and the full extent of the valley networks may not be represented by the valleys visible today [3,11].

The drainage densities we determined for valley networks across Mars range from 0.053 km^{-1} to 0.14 km^{-1} (mapped at ~1:500,000 scale), which are comparable, albeit on the low end, to the *Carr and Chuang* [12] terrestrial drainage densities that were mapped in a similar method with Landsat 4 images. Since the determination of drainage density is strongly influenced by the identification of small tributaries, Mars will be prone to smaller densities due to the limits of image resolution and 3.5 Ga of surface modification, whereas Earth will be prone to higher densities due to their younger, active state and the presence of water and vegetation that aids in identification of small tributaries [e.g. 3,10]. The similarity in drainage density between martian and terrestrial drainage systems supports the hypothesis that the martian valleys were formed, at least in part, by precipitation [e.g. 2] and the somewhat lower martian values likely reflect not only differences in the conditions of their formation but also the greater difficulty in their identification.

Comparing the martian drainage densities with latitude, longitude, elevation, and age shows very little correlation. This indicates other variables, such as the resistance of the surface layer to erosion, the infiltration capacity of the soil, the frequency and/or duration of rainfall events, and the preservation state of the valleys, played a bigger role in determining the density of the drainage systems.

Since drainage density is strongly dependent on the ability to identify even the smallest tributaries, it is expected that this should create a bias toward higher drainage densities for younger, more pristine networks, assuming the conditions for drainage network formation were constant during subsequent formation periods. Indeed, many of the older networks have a greater amount of erosion and infilling, but they do not have correspondingly low relative drainage densities. Figure 1 shows a general lack of correlation between drainage density and age. Rather drainage density appears somewhat better correlated with preservation state, though this too is not without exception. Four of the five more pristine networks have higher drainage densities relative to the others, while the more degraded networks have lower drainage density with the exception of three of the four older networks. Since it appears the older networks have experienced multiple periods of formation (see below), it follows that this has contributed to their overall greater density, particularly if a loss in density with increased degradation is considered.



▨ Heavily degraded throughout most of valley network

⬚ Pristine throughout most of valley network

▯ Older valley network

1. 2°N, 34°E west branch
2. 12°N, 43°E
3. 10°S, 127°E
4. 15°N, 30°E
5. 6°S, 45°E
6. 2°N, 34°E east branch
7. 0°N, 23°E
8. 22°S, 10°W
9. 7°S, 3°E
10. 12°S, 12°E
11. 3°S, 5°E
12. 10°S, 14°W

Figure 1. The drainage densities of all the valley networks analyzed are shown here in approximate chronological order according to the corresponding *N(1)* value, with youngest on the right. Larger drainage densities are calculated for valley networks with pristine morphology and those with crater size- frequency distributions that suggest they are older.

Valley Network Age Determination: Using THEMIS daytime IR and MOLA topography data in ArcGIS®, and following the method outlined by *Tanaka* [13] and *Hoke and Hynek* [14,15] for counting craters along narrow linear features of limited surface area, we counted superposed craters for each valley network. This ensured accurate crater counting that represented the cratering population since the end of valley formation. All craters on the surrounding surface that did not overlap the networks or were stratigraphically below the networks were excluded in the count. Because of the variability of ejecta blanket preservation, only craters whose rims overlapped the valley network were counted. This provides a minimum age bound on these valley networks.

The crater size-frequency distribution for each valley network was analyzed and production and resurfacing regimes, if applicable, were identified for each. The production regime for the range of crater diameters used in this work (1 km to ~23 km) has a slope of approximately -1.8 on a log-log cumulative crater density vs. crater diameter plot [16,17]. A shallower crater density slope suggests that a period of erosion or burial occurred sometime in the valley network's past that preferentially obliterated smaller craters, as described by *Melosh* [16] and others. Because of the cumulative effect of cratering on planetary surfaces, the oldest valley networks in this work are interpreted as those which have greater crater densities at all crater diameters and/or a downturn in crater density at intermediate crater diameters.

The crater size-frequency distribution plots show that all these valley networks ceased formation toward the end of the Late Noachian or at the beginning of the Early Hesperian, consistent with results from *Hynek and Phillips* [1] and *Fassett and Head* [7]. Our ages do not extend into earlier martian history, nor significantly into the Hesperian, and the spread in these ages indicates they did not all form, or cease formation, at the same time.

Using the equation in *Ivanov* [18] that relates the crater number at 1 km diameter craters, *N(1)*, with absolute age, the difference in age between the oldest and youngest valley networks analyzed in this work is ~200 Myr. Within this range are valley networks that appear to be coeval and those that have distinctly separate ages, including two branches of the same networks that formed ~90 Myr apart. Our *N(1)* values correspond to absolute ages of 3.58 to 3.79 Ga (Table 1) and are compared in Figure 2 with the ages for six of these valley networks calculated by *Fassett and Head* [7]. The *Fassett and Head* [7] values for the same valley networks we analyzed differ by 10-210

Myr, depending on the network, with most of the *Fassett and Head* [7] ages being older than ours.

For most of these crater-ages, the error bars overlap with those of the nearest temporal neighbor(s), either indicating that they formed coevally or that the precipitation moved over shorter timescales than our data can distinguish. *Colaprete et al.* [19] showed that regional variations in rainfall would be expected during periods of warmer/wetter climate, consistent with what we see with the ages of valley network formation. Locations of rainfall could vary depending on the presence of surface bodies of water, temperature, pressure, obliquity, etc. It is beyond the resolution of our data to say whether the climate was continuously warmer and thicker during the end of the Noachian and the location of rainfall changed over the ~200 million years these networks span (based on their N(1) values), or if instead the global climate was changing on short timescales, producing shorter, perhaps more intense episodes of temporarily warm/wet conditions that allowed valley network formation to occur in localized regions.

Discussion: The results from this research place precipitation-driven formation of these martian valley networks in the Late Noachian and earliest Hesperian epochs. Several factors were present toward the end of the Noachian that likely created a climate conducive to valley formation that may or may not have been present earlier in martian history and only intermittently in more recent martian history. Most notable is outgassing from the Tharsis rise, which may have played a major role in causing the climate change that allowed valley network formation to occur during the Late Noachian [21]. Analysis of tectonic, magnetic, gravity, topographic, relative stratigraphic, and crater density data place the formation of most of the Tharsis load prior to the end of the Noachian [17,20-22]. Valley network formation likely followed a majority of the Tharsis formation since the drainage pattern of the valley networks on the ancient surfaces on Mars follow the long wavelength topography created by the Tharsis load [21,23]. Many researchers have determined that the quantities of CO_2 and H_2O released during Tharsis formation may have been sufficient to warm the atmosphere during the Late Noachian to the point that liquid water was stable at the surface [21,24]. Precipitation and valley incision may have coincided with a balance between episodes of volcanic outgassing and the steady loss of atmospheric constituents to the surface and space. Alternatively the atmosphere may have been sufficiently stable to allow a more continuous period of clement weather while the location of precipitation moved in time with changes in global circulation patterns, local atmospheric pressure, surface topography, insolation, and other variables [10].

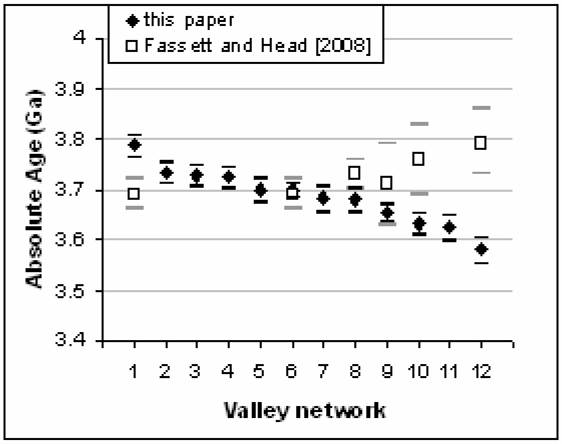


Figure 2. Absolute ages from *N(1)* values for the valley networks in this work show that the end of valley network formation occurred between about 3.58 and 3.79 Ga, which falls within the Late Noachian and Early Hesperian. Comparison with ages from *Fassett and Head* [7] for six of these networks shows similar results with a few of our ages, particularly for the east branch of 2°N, 34°E (#5, Naktong). Three of these networks show distinctly different ages between our results, which is a result of differences in our age-determination techniques.

Regardless of the trigger for climate change, valley network formation in large regions of the ancient highlands of Mars appears to have ceased at the Noachian/Hesperian boundary. While atmospheric concentrations of CO_2 and H_2O would have been lost to space throughout the Noachian through solar wind stripping, impact ejection, and thermal escape, the loss rate would have increased as the internal magnetic field disappeared [23]. The timing of this event is generally placed sometime during the Noachian [25-28] and is very likely associated with the climate change that marks the end of the Noachian epoch [23]. Additionally, the formation of carbonates and hydrated minerals and the growth of the polar caps and subsurface ice reservoirs would have further reduced atmospheric concentrations of CO_2, H_2O, and other greenhouse gases [23,29-31]. Together with a decreasing impact rate and a decline in Tharsis volcanic activity, these factors would have led to the loss of enough atmosphere to end precipitation-related valley network formation within a timespan of less than a few hundred million years [21].

Conclusions: The valley networks in this study are characterized by morphologies and drainage densities that suggest they formed primarily by precipitation. Some of these networks appear to have experienced multiple periods of formation, predominately from precipitation-dominated valley formation and also from a few localized sources of water including paleolakes and groundwater sapping at springs.

The valley networks also appear to be in different stages of preservation, with some networks highly eroded and/or in-filled while others appear pristine. This preservation state affects the calculation of drainage density so that the more degraded networks have an overall lower density. Exceptions to this lie with the older networks, which are interpreted as having experienced multiple periods of formation that likely contributed to their greater drainage densities.

Determining the ages of actual valley formation through crater counting on the valley networks themselves provides much more precise constraints on the timing and duration of warmer, thicker atmospheric conditions than analysis of stratigraphic and cross cutting relationships. Using a method tailored for counting craters on narrow linear features and performing crater counting only on large valley networks, we were able to improve the crater counting statistics and estimate ages for these valley networks. The results show that the Late Noachian and beginning of the Early Hesperian were at least periodically warm enough to support an active hydrological cycle on large regions of the ancient martian surface. Our ages do not extend into earlier martian history, nor later than the Early Hesperian, and the spread in these ages indicates they did not all form, or cease formation, at the same time. Within the span of ~200 Myr that passed between the oldest and youngest of these valley networks are those that appear to be coeval and those that have distinctly separate ages.

These results support two possible climate scenarios. The ancient martian climate may have produced continuously warmer and thicker atmospheric conditions during the end of the Noachian while the location of rainfall changed in response to other parameters. Alternatively, the ancient global climate may have been changing on small timescales, producing shorter, more intense episodes of temporarily warm/wet conditions that allowed valley network formation to occur in localized regions. Regardless, it is apparent that precipitation was neither global nor continuous. Rather, zones of precipitation appear to have roamed throughout the equatorial regions of the ancient martian surface, sometimes returning to previously rainy regions.

The timing of valley network formation on ancient Mars appears to coincide well with the suggested accumulation of CO_2 and H_2O from Tharsis outgassing, providing a possible explanation for the climate change necessary for liquid water to be stable on the surface of Mars and the formation of complex valley networks. As Tharsis activity dropped and atmospheric constituents became more vulnerable to solar wind stripping with the loss of the intrinsic magnetic field, precipitation waned and valley incision on these ancient highlands of Mars stopped at the Noachian/Hesperian boundary.

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