MARS' CLIMATE HISTORY AS INFERRED FROM VALLEY NETWORKS ON VOLCANOES.

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Introduction: Recent Mars Odyssey spacecraft data allow well-constrained absolute age determinations of Martian volcanoes. These data also allow an unprecedented examination of the valley networks that occur on the volcanoes. Morphologic arguments suggest most of these valleys were formed by precipitation and surface runoff, although there are cases that appear hydrothermal in origin. Thus, we can use the precipitation-formed valley networks and their characteristic drainage density fluxes through time to provide inferences into the climate history of Mars. Analysis of Thermal Emission Imaging System (THEMIS) data suggests a sharp decrease in precipitation throughout the Late Noachian and Hesperian epochs. After the Hesperian period, valley formation due to precipitation became essentially non-existent and volcanic activity became seemingly isolated to the Tharsis region. The few Amazonian-aged valleys located on the youngest Tharsis volcanoes most likely formed through groundwater processes—namely hydrothermal activity. Here, we constrain the ages of all Martian volcanoes with discernable valleys based on crater density analysis to study these uniquely occurring networks.

Background: Since the initial discovery of Martian valley networks, many theories suggesting their origins have been formulated and discussed: surface runoff caused by precipitation; groundwater processes and hydrothermal activity; and melting/erosion at the base of snow or ice sheets [e.g., 1-3, respectively]. The majority of these valley networks are distributed across the older Southern Highlands; generally dating >3.7 Ga ago. However, some of the valley networks have incised younger Hesperian (~3.7-3.0 Ga) and Amazonian (<~3.0 Ga) age terrains and they are often occur on volcanoes. Some of these valleys likely formed in hydrothermal settings [2] and it is possible that others represent transient climate change events induced by massive flooding [4].

Methods: To investigate the relationship between precipitation and time, the THEMIS daytime IR global mosaic [5] and Mars Orbiter Laser Altimeter (MOLA) data [6] were used to identify and map valley networks on all Martian volcanoes. We then inferred the origins of valley networks (namely, precipitation-fed runoff vs. hydrothermal) from the valleys' morphometry and surrounding geological context. We also measured drainage densities and investigated the maturity of the valley systems. Subsequently, volcano surfaces were age-dated through measurements of crater density which were then related to the Martian isochrons of Hartmann and Neukum [7]. Craters >5 km were primarily adopted from previous studies [i.e., 8], which used Viking data. We used higher resolution THEMIS data (256 m/pix) to enhance this count and add smaller crater diameter bins, thereby increasing the accuracy of surface ages compared to many previous studies. The age of each volcano with valleys was inferred from cumulative crater plots. With the surface ages of 18 major volcanoes determined along with identification of precipitation-fed systems, it became possible to analyze valley network formation due to precipitation over the course of Martian history.

Results/Discussion: The results indicate a sharp decrease in drainage density over time, similar to valley network formation in the Southern Highlands [9]. Figure 1 shows a normalized plot of drainage density vs. time. The relatively high drainage densities, valley morphology, and complicated network patterns on surfaces imply surface runoff from precipitation (e.g. Fig. 2). The majority of our drainage densities on Noachian era volcanoes are similar to values calculated for

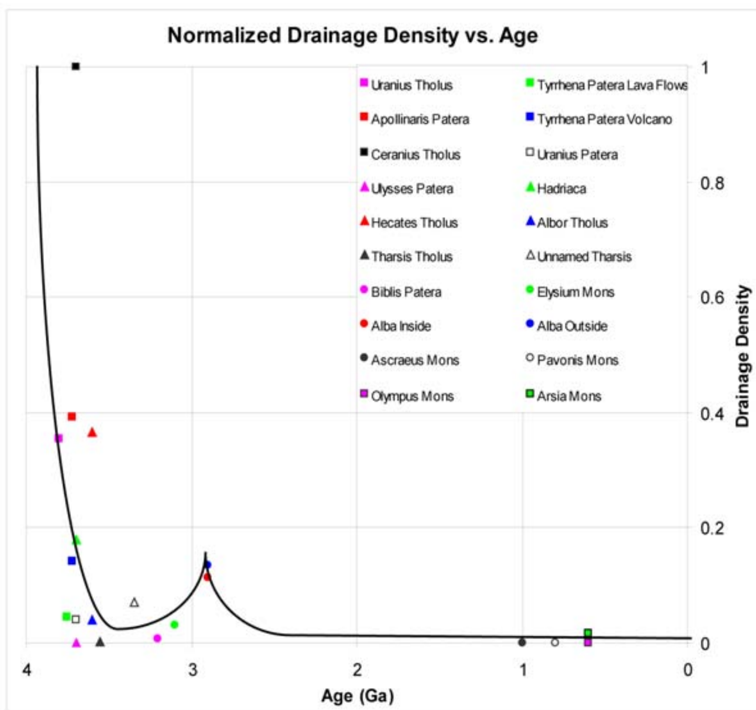

Figure 1: The change in normalized density over time. Ceranius Tholus, the densest volcano, has a value of 1.0. Each other volcano is represented as a fraction of the drainage density of Ceranius Tholus. The line that we have inserted is our interpretation of overall drainage density flux over time.We must note that, with the exception of the young Tharsis volcanoes, the data points represent predominantly precipitation-fed networks.

dense Southern Highland's networks also thought to have been formed during warm and wet conditions [1].

Since 2.9 Ga ago, drainage densities on more recent volcanoes approaches zero (Fig. 1) and the complexity of the few valleys observed decreases significantly (few tributaries, low bifurcation ratio, etc.). Furthermore, most valleys which formed after this time tend to appear related to non-impact pit crater chains associated with volcanic features. The northwestern flank of Arsia Mons serves as an example (Fig. 2). These traits are characteristic of valleys formed by groundwater processes (hydrothermal activity) as opposed to surface runoff from precipitation, consistent with Viking-based results of Gulick [2]. The change of valley morphology over time shows the abrupt decline of the putative warm and wet Noachian climate, in which global precipitation was frequent enough to erode and modify volcanoes, into the cooler dry climate found today.

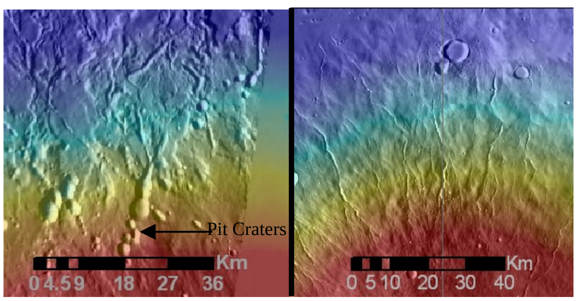

Figure 2: Comparison of valley networks believed to have been formed by hydrothermal processes (left) and surface runoff/precipitation (right). The image on the left is taken from Arsia Mons—age of 0.6 Gyr, drainage density of 2.4×10^{-3} km^{-1}. The image on the right is taken from Hecates Tholus—age 3.6 Gyr, drainage density of 5.1×10^{-2} km^{-1}. Colors represent MOLA topography (red = high; blue = low).

The Martian volcano with the highest drainage density is Ceranius Tholus with a density of 0.14 km^{-1} and an age of 3.7 Ga. It is noteworthy that some volcanoes had no detectable valleys at THEMIS IR resolution (e.g. Ascraeus Mons, Pavonis Mons, and Olympus Mons—ages 0.6, 1.0, and 0.8 Ga, respectively). It is important to note that while the THEMIS visible data (18 m/pix) shows valleys on Ascraeus Mons, the IR daytime global mosaic used in this work does not. However, the higher resolution images suggest that these valleys are likely hydrothermal in nature and do not reflect precipitation.

The volcanoes on Mars record the youngest fluvial activity on the planet, [9] and several post-date the putative warm and wet Noachian epoch. Baker et al. [10] suggested that many valleys—on Alba Patera especially—may have formed due to precipitation when global climate became temporarily warm and wet as a result of the massive flooding and ponding of water that occurred during outflow channel formation. A rise in temperature and vapor pressure would have allowed regions with higher elevations adjacent to the transient ocean to be incised with precipitation-fed valleys. While somewhat sporadic, the majority of outflow channels likely formed in the Late Hesperian to Early/Middle-Amazonian epochs [11]. Our results may support this theory of youthful valley formation (Fig. 1). The one volcano (Alba Patera) whose surface formed during high outflow activity does in fact show a spike in what we infer to be precipitation-fed valley drainage systems relative to the overlying exponential decay of drainage density through time (Fig. 1). However, this conclusion is limited by only one volcano dated to the time period of significant outflow channel activity.

As Figure 1 shows, there is a lack of volcanic surfaces between 2.9 and 1 Ga ago. The volcanic surfaces which formed after 3.0 Ga are all found in the Tharsis region (Olympus Mons, Arsia Mons, Pavonis Mons, Ascraeus Mons). This implies that during the Amazonian epoch, volcanic activity became mainly isolated to the Tharsis region. The final spurts of large scale activity were between 1.0 to 0.6 Ga ago.

In summary, we used THEMIS data to study valley networks that occur globally on volcanoes and determine which ones were likely formed by precipitation and surface runoff as opposed to hydrothermal activity. Crater density measurements were used to date the ages of the surfaces on which the valleys occur. Analysis of these results allow us to infer climate change through time on Mars. Our results show that valley formation was precipitation-fed in the Noachian and rapidly died off over time. Our results may support the idea of transient climate change induced by large flooding events [10], but the data are limited during this time period. The youngest valleys found on Martian volcanoes occur in the Tharsis region, are likely to be hydrothermal in origin, and date from the Late Amazonian epoch.

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