VALLEY NETWORK FORMATION ON THE ANCIENT HIGHLANDS OF MARS OCCURRED IN THE LATE NOACHIAN AND EARLY HESPERIAN EPOCHS M. R. T. Hoke[1,2] and B. M. Hynek[1,3], [1]Laboratory for Atmospheric and Space Physics [2]Dept. of Astrophysics and Planetary Sciences [3]Dept. of Geological Sciences (University of Colorado/LASP, 392 UCB, Boulder, CO 80309-0392, hoke@lasp.colorado.edu & hynek@lasp.colorado.edu)

Introduction: Valley networks provide a record for the location, quantity, source, and timing of flowing water on the surface of Mars. Determining the ages of individual valley networks that appear to have formed primarily by precipitation and surface runoff through crater density analysis provides constraints on the timing and duration of warmer, thicker atmospheric conditions.

Method: Fourteen of the largest valley networks in the Terra Sabaea, Arabia Terra, Meridiani Planum, and Terra Cimmeria regions of Mars were mapped through visual inspection of coregistered THEMIS daytime IR and MOLA data in ArcGIS. These networks were then individually crater-age dated and their crater size-frequency distributions were analyzed to understand the timing of the end of their formation.

Following the method outlined by *Tanaka* [1] and *Hoke and Hynek* [2] for counting craters along narrow linear features, craters 1 km in diameter and larger that were superposed on the valleys were counted and binned into increments of $\sqrt{2}D$. Crater counts per bin ranged from 1 to 91, depending on valley network and crater size. The cumulative crater densities of each valley network were plotted vs. the corresponding weighted mean crater diameter on a logarithmic plot and compared to Tanaka's isochrons [3] to assess the approximate age of each valley network.

Counting small craters for age-dating is complicated by the presence of secondary craters, as including secondaries increases the crater density at those diameters and may result in the interpretation of an older age. For crater populations affected by secondary craters one should expect an upturn in the crater size-frequency distribution to slopes of approximately –3.5 to –5, which is greater than that for the primary crater production function of approximately –1.8 to –2 [4-7]. Generally speaking, secondaries become statistically significant in crater counts at sizes less than ~0.4% the diameter of the primary [4, 6-8]. *McEwen and Bierhaus* [9] show that for the Moon, the crossover from primary-dominated to secondary-dominated crater populations occurs at ~1 km, as hypothesized by *Shoemaker* [4]. For martian surfaces having ages near the Noachian/Hesperian boundary, secondaries should become statistically significant at diameters of ~600m (from craters ~150 km in diameter) [10]. By excluding obvious secondary craters (oblong shape, clustered, rayed) and craters smaller than 1 km in our counting, we feel our results provide crater ages that are not significantly affected by the presence of secondary craters.

By limiting our study to only large valley networks, our crater counts are high enough that we have sufficient data points to create crater size-frequency distributions that not only display the expected production regimes, but also show resurfacing regimes characterized by a downturn in crater density at intermediate crater diameters. Because of this, we avoid needing to fit our data to the Hartmann or Neukum production functions as other researchers have done [*e.g.* 11], which have large uncertainties in the 1 km to 16 km crater diameter range.

Results: Five of the valley networks examined, including 15°N, 30°E (Scamander); 2°N, 34°E (Naktong); 7°S, 3°E; 3°S, 5°E; and 10°S, 127°E, have crater size-frequency distributions that include a resurfacing or reactivation regime. These networks have greater crater densities at large crater diameters than the other networks, and they have a turndown in slope at intermediate crater diameters that the other networks do not. This turndown indicates that they have experienced some erosion and/or infilling at some point after their primary valley-forming event that has preferentially removed smaller craters up to a given crater diameter, or that the valley network includes two populations of craters, accumulated after two periods of valley network formation. For most of the valley networks, the slope of the crater size-frequency distributions are approximately –1.74 to –2.34, which correspond to production regimes. Whereas, the resurfacing/reactivation regimes have much shallower slopes at approximately –0.89 to –1.37. None of the slopes approached values (–3.5 to –5) that correspond to contamination by secondary craters. All of these reactivated networks have crater densities at smaller crater diameters that indicate the modification events occurred within the Late Noachian and are coincident with the formation of the other valley

Table 1. Comparison of cumulative crater numbers, *N(2)*, for valley networks on the ancient highlands of Mars with those of the martian epochs places the timing of the end of formation for these valley networks at the end of the Late Noachian and into the Early Hesperian.

Valley network	**Cumulative crater number at 2 km *N(2)*, per 10^6 km^2**
15°N, 30°E, Scamander	1699 ±279
2°N, 34°E, Naktong	1634 ±170
12°N, 43°E	1522 ±304
10°S, 127°E	1500 ±279
22°S, 10°W, Parana	1491 ±282
9°S, 118°E	1232 ±233
12°S, 12°E, Evros	1060 ±168
10°S, 14°W	844 ±139
Martian epoch boundaries	***N(2)*, per 10^6 km^2, for a) Hartmann and b) Neukum production functions [11]**
Middle/Late Noachian	a) 4334, b) 1862
Noachian/Hesperian	a) 996, b) 954
Early/Late Hesperian	a) 623, b) 596

networks. Therefore, these five valley networks are interpreted as having initially formed prior to the others and then experienced reactivation as the younger valley networks formed.

To allow comparison with the Hartmann and Neukum isochrons (from [11]), our *N(2)* crater numbers and those that correspond to the epoch boundaries are given in Table 1. Valley networks that had low *N(2)* values due to resurfacing regimes (7°S, 3°E and 3°S, 4°E) or insufficient crater counts (6°, 45°E; 0°N, 23°E; 18°S, 18°E; 6°S, 128°E) were left out of Table 1. Our *N(2)* crater numbers range from 844–1731 per 10^6 km^2, placing the end of formation for these valley networks in the Late Noachian and Early Hesperian.

Discussion: The results from this research place the end of precipitation-driven formation of these martian valley networks in the Late Noachian and earliest Hesperian, consistent with results from *Fassett and Head* [11] and *Hynek and Phillips* [12]. 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 of *Ivanov* [13] that relates crater number, *N(1)*, with absolute age, the difference in age between the oldest and youngest valley networks in Terra Sabaea, Arabia Terra, and Meridiani Planum analyzed in this work is ~210 ±50 Myr. Within this range are valley networks that have distinctly separate ages, and those that appear to be coeval.

On Earth, a rainy region may experience changing levels of precipitation over time, driven by changes in topography and relative locations of bodies of water, changes in atmospheric characteristics, and/or changes in orbit and obliquity. Likewise, precipitation is not expected to have occurred everywhere simultaneously on Mars. *Colaprete et al.* [14] showed that regional variations in rainfall would be expected during periods of warmer, wetter climate. This variability in precipitation is especially important for a hypothetical early Mars without a large ocean to constantly supply water to the same region.

Both the morphologies and crater ages of these valley networks indicate precipitation did not extend everywhere simultaneously on Mars, and regions of precipitation moved around during the Late Noachian and Early Hesperian. It is beyond the resolution of our data to say whether the atmosphere was continuously warmer and thicker during the end of the Noachian and the location of rainfall changed over the ~210 million years that these networks span, 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.

The lack of valley networks in this large region older than the Middle of the Late Noachian is surprising. This observation could indicate that valley network formation in these regions did not occur earlier in the Noachian, or that any traces of valleys whose formation ceased earlier in the Noachian have been erased. If the valleys from older episodes of formation have been so modified by erosion, infilling, impact craters, and subsequent valley network formation episodes that they are no longer represented by individual, large, connected networks, our use of only the largest valley networks in this region may bias our results. However, *Fassett and Head* [11], who were less limited by valley network size, still found most of the ancient valley networks they analyzed had Late Noachian crater-ages. When they applied their data to Hartmann production functions [3], it resulted in no networks older than Late Noachian with the oldest valley network (Naro Vallis) having an age of 3.81 Gyr [11].

The timing of valley network formation on ancient Mars appears to coincide well with the accumulation of CO_2 and H_2O from Tharsis outgassing [e.g. 15, 16], providing a possible explanation for the climate change necessary for liquid water to be stable on the surface of Mars and the formation of dense valley networks. However, this environment was not constant; the areas of the surface receiving rainfall changed over the timescales of tens to hundreds of millions of years. These zones of precipitation appear to have roamed throughout Terra Sabaea, Arabia Terra, Meridiani Planum, and Terra Cimmeria, sometimes returning to previously rainy regions. As Tharsis activity waned and atmospheric constituents continued to be lost to space [17], the surface, and the subsurface [16-20], precipitation waned and valley incision on these ancient highlands of Mars stopped at roughly the Noachian/Hesperian boundary.

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