MARS VALLEY NETWORKS: CHRONOLOGY AND ENVIRONMENTS. C. I. Fassett, J.W. Head, and J.L. Dickson, Box 1846, Dept. of Geol. Sci., Brown Univ., Providence, RI 02912. (Caleb_Fassett@brown.edu)

Introduction: The recognition, mapping, and interpretation of valley networks has been an ongoing scientific endeavor for more than 30 years [e.g., 1]. Recent improvements in image coverage and resolution have improved our understanding of valley networks and associated lakes and sedimentary deposits. Moreover, multispectral and hyperspectral instruments such as THEMIS and CRISM have revealed that certain valley network-related deposits have interesting mineralogy, such as phyllosilicates which have been fluvially transported [2] and possible chloride salts in basin floors [3].

Along with examining valley networks in unprecedented detail, there has also been some progress in improving the time constraints on when valley networks were active [4]. Placing valley networks within a chronological framework is important if the formation of valleys is to improve our knowledge of the evolution of the surface environment and martian climate over time. In this abstract, we summarize some recent findings regarding the chronological constraints on valley formation, the environments in which they formed, and discuss a few specific new examples of valleys which are unusually young and may help inform us about the variations in valley formation conditions over time.

Our General Chronological Approach: The most commonly applied technique for finding the age of valley networks is to obtain a reliable age for the surface that they incise. Mapping using Viking data originally led workers to the conclusion that most valleys are ancient (Noachian in age) [5,6], especially the valley networks that are the most integrated and subdivide the greatest areas. The primary limit of this method is that it requires careful delineation of what unit is actually incised, which can be difficult in highland regions that have undergone extensive erosion or gradation; in the best case scenario, this method only gives an upper limit on valley age. Thus, different interpretations of what units are actually incised (and their stratigraphic position) can lead to alternative interpretations of when valley network formation occurred; indeed, some workers using this methodology have thus argued that many valleys are actually young [7]. Thus, we have taken a different approach to measuring the valley ages.

Buffered Crater Counting. Instead of mapping the unit that specific valley networks incise, we count around valleys in a series of buffers, as has been attempted before for other planetary surface features [8] and similar to a technique first described by Tanaka [9]. This method takes advantage of the fact that large craters subtend a much larger area than small ones. We first map the valley we wish to examine, and then find all craters clearly superposed upon the valley within an area appropriate for its diameter. For each crater (and its ejecta), a stratigraphic judgment is required, and we assume that any topographic barrier (e.g., a crater rim or its ejecta) superposed on the valley must have formed after valley activity ceased. Only craters which are clearly superposed are included, so our results should be a robust minimum age/period (lower limit) for integrated fluvial activity in the valley system.

For a given crater size D, we count in a buffer of size 1.5D from each valley side. In doing so, we are assuming that it is possible to determine stratigraphic relationships for craters with rims within one crater diameter of the valley walls (consistent with expectations from scaling laws that the extent of continuous ejecta is ~1D [10]). The total count area A that we use for a linear segment of a valley (length L) with craters of diameter D is A(D)=(3D+Wv)L, where Wv is the valley width. Count areas are computed for a given crater size by applying the ArcMap buffer function to the mapped valleys (taking into account that buffers for multiple valley segments can overlap). We have tested this methodology with a more stringent buffer size of 0.5D (requiring that the valley falls directly within the crater rim). The stricter buffer gives results that are consistent with the 1.5D buffer, although it limits the count area, hence decreasing our counting statistics.

Period Boundary Consistency. A challenge for crater counting on early Mars surfaces is that the definition used for the period boundaries is somewhat unclear, which can alter the relative age assignment of features or units. This difficulty arises because the original period boundaries were defined assuming a different shape for the crater-size frequency distribution [11] than recent isochron systems [12,13]. The way that workers address this problem has unfortunately ranged somewhat widely, leading to inconsistency in period assignments even for comparable crater frequencies. To combat this issue, we adopt the convention of using the original Tanaka boundary definitions [11] referenced to a specific cumulative number of craters at diameter D=2 km in the Amazonian period boundaries, 5 km for the Early Hesperian/Late Hesperian and Noachian/Hesperian boundaries, and 16 km for the boundaries of the Noachian subperiods (see Table 1). Then, we use the shape of the crater-size...
frequency distribution (isochrons) defined by particular workers to expand the period boundaries beyond these reference points. This pins the period boundaries at specific sizes to be the same across isochron systems, so different assumptions about the shape of the production function do not alter the relative period determination. We believe this is preferable to attempting to tie the period boundaries to some absolute age, since these model ages are derived parameters with significant systematic uncertainties, unlike the crater-size frequency distributions of various features which can be directly measured and compared.

**Chronological Results: Highland valley networks.**

We examined 26 separate specific valley networks, representing approximately 25% of the total length of mapped valleys in the highlands. Most valleys we examine were chosen to be outside the high latitudes (>30° in each hemisphere), where mantling material makes crater counts and stratigraphic determinations more uncertain (an exception is Warrego Valles, which we wanted to consider because of the detailed work that had been done on this region in the past).

In every instance, the superposed crater population resulted in a best fit age in the Early Hesperian or older, with most ages clustering around the Noachian/Hesperian boundary (Fig. 1). The statistical nature of these results means they can be interpreted in several ways. One possible interpretation is that all of the variability is a result of counting statistics, and that valleys ceased activity at essentially a single point in time. In this view, all valleys have a best fit age that falls almost exactly at the Noachian/Hesperian boundary; the best fit Hartmann and Neukum ages respectively of AH=3.53 Gyr or AN=3.75 Gyr, with N(5)=214 (where N(5)=200 is the definition of the Noachian/Hesperian boundary [11]).

However, an alternative scenario is that some of the valleys that have younger best fit ages are in fact younger, and that the spread in crater frequencies reflects the fact that some highland valleys that terminated activity in the Noachian while others persisted into the Early Hesperian. Tentative support for this second interpretation comes from two observations: (1) some of the ‘younger’ valley networks (Early Hesperian best fit age) are among the densest, most well-preserved systems (such as those in Margaritifer Sinus [14], Parana/Loire has AH=3.49 Gyr or AN=3.73 Gyr, with N(5)=188); and (2) in some instances, valleys with young ages also have stratigraphic evidence suggesting Early Hesperian activity; for example, stratigraphic observations have supported an Early Hesperian age for major activity in Naktong Vallis [15] (where our counting also gives an Early Hesperian age).

Whichever interpretive scenario is correct, we believe that highlands valleys date to the Early Hesperian or before, with all major highland valley systems having formed by AH>~3.45 Gyr and AN>~3.7 Gyr (Neukum system). If major valley network systems in the highlands had been active more recently (Amazonian or Late Hesperian), it would have been apparent based on their superposed crater population. Indeed, in a few exceptional cases (none of which are ‘classic highland valleys’), this is in fact what we observe.

**Young valley networks.** Several workers [e.g., 16, 17] have identified valley systems that are apparently young, and we made a particular attempt to derive ages for four of these systems. Our crater counts support the idea that the valleys on Ceraunius Tholus, Hecates Tholus, Alba Patera, and the plateaus above Valles Marineris are young (Late Hesperian to Early Amazonian). In each instance, it appears likely that the formation of these young valleys can be understood as a local phenomenon that does not require global climate excursions. HiRISE and CTX have also provided new evidence for locations and environments on Mars that appear to have valleys formed in the more recent past. We discuss a few such examples below.

**Surface Conditions for Forming Ancient Highland Valleys:**

The precise conditions required to form the highland valley networks is a longstanding scientific debate that remains unresolved. However, the findings of recent missions have helped clarify some of the environmental factors required: (1) precipitation of some form is necessary to form the observed valleys [e.g., 18]. Valleys commonly begin at drainage divides where either direct precipitation or precipitation-forced recharge is required for surface flow to occur. (2) A variety of arguments (channel geometry [19], basin characteristics [20,21], and inferences from sedimentary deposits [22,23]) suggest that surface flows had terrestrial-like discharges and persisted for many thousands of years (probably 10^5-10^6 years), but also may have been intermittent. (3) Significant amounts of water were in the surface hydrosphere at certain points of time. Evidence exists for >200 paleolakes with outlets which must have been open basins at one time [24]; in many instances, these open basins formed lake chains (requiring that basins higher in a chain were filled at the same time as those at lower elevations). These observations imply radically different surface conditions than those on Mars today.

**Geological Environments with Younger Valleys:**

Recently, we have begun to recognize a series of small valleys on Mars using CTX data in apparent association with ice-rich environments [25]. These are typically at much smaller scale than highland valleys and confined to certain locales. Because of their small extent and the difficulty applying the buffered crater
counting technique to such small valleys, establishing the chronological framework for these valleys can be challenging unless the local stratigraphic framework is clear. We discuss two such locations below.

**Lyot Crater.** Lyot Crater is a ~215 km peak-ring impact basin in the northern lowlands of Mars (50°N, 30°E) and one of the most prominent young impact basins on the planet. Stratigraphic analyses of Viking Orbiter data concluded that the Lyot impact event occurred in the Amazonian epoch [26]. The interior of the basin has a pervasive mantling deposit at CTX resolution characterized by a stipped and hummocky texture and diffuse margins. Along the Lyot crater rim and central peak ring, deposits interpreted to be glacial landforms are observed, similar to those mapped in the adjacent Deuteronilus Mensae [27]. These features contain convex outward ridges, convex upward profiles, and other surface features suggestive of debris-covered glaciation; they are especially prominent along the southern rim of Lyot, where a set of three broad lobate debris aprons trend downslope from a highly-modified portion of the crater rim and extend onto the crater floor (Fig. 2).

Strikingly, extending away from some of these lobes and cutting the stippled mantle on the floor of Lyot are small, sinuous valleys, ranging in length from short, 2 km long isolated valleys up to 50 km long networks. Valleys follow the local topographic gradient, consistent with a fluvial origin. In some locations, valleys braid and small islands are observed on some valley interiors. These valleys in Lyot terminate either by gradually tapering into the mantling unit (with no discernible deposits), or, in the case of some larger valleys, by depositing degraded fans at breaks in slope.

To help constrain when the Lyot valleys were active, we used HRSC data to reexamine (1) the formation age of Lyot, for which we obtain an Early Amazonian age ($A_N \sim 3.3$ Gyr, $A_T \sim 1.6$ Gyr), and (2) the age of the incised, stippled mantling unit, for which we derive a Middle Amazonian age ($A_N \sim 1.5$ Gyr, $A_T \sim 0.8$ Gyr). Thus, the age of the Lyot valleys imply they formed well after the cessation of highland valley networks.

**Valleys on Young Crater Ejecta.** In several locations on Mars, small valleys appear to be found on crater ejecta that are often easily apparent only at CTX or HiRISE resolution (Hale crater, [28]; Sinton Crater [29]). We have recognized a few other examples on the ejecta of craters of sizes from 7-30 km, (e.g., a 25-km crater at 143W,45S (Fig. 3); the 7 km crater at 130E, 36S). As yet, there have been no detailed survey of this phenomena, but the examples which we are presently aware of are concentrated in locations where ground ice and/or surface ice may be likely in the recent past (latitudes $>30^\circ$). Although some valley forms can result from impact melt eroding the surface itself rather than water, in our view, the nature of these small valleys is generally more consistent with fluvial erosion, sediment transport, and deposition. More work is necessary to document the location of these features and understand their formation conditions.

**Sources of water to these young valleys:** Possible sources for water for these young valleys in Lyot and on impact ejecta include (1) direct melting of near-surface or surface ice immediately following impact, (2) hydrothermal or groundwater activity, perhaps enabled by residual heat form the impact event, or (3) environmental conditions conducive to melting due to the microclimate of the impact basin itself. The first of the two scenarios is consistent with most of the valleys we observe on the ejecta of young craters.

In the case of Lyot crater, however, it can be more reasonably explained as a microclimate, since the valleys are located inside the basin itself and incise a surficial mantle which appears to postdate Lyot by at least hundreds of millions of years (at minimum, >800 Myr based on our model ages). Unlike the valleys on ejecta, the valleys at Lyot can be traced directly to likely glacial sources. Since Lyot crater is among the highest surface pressure (minimum elevation ~7000 m below the datum) and can achieve peak surface temperatures above the freezing point of water [30] when Mars is at high obliquity (60°), as is likely in the distant past [31], it may be a favored location for climate related melting of ice in the Amazonian.

**Conclusion:** The small fluvial forms being recognized on young surfaces on Mars show that it has a rich valley formation record which extends beyond the large-scale, ancient valley networks to epochs closer to today. However, these observations remain consistent with a major shift in the surface conditions which enabled valley formation from the Noachian to the Amazonian [4]. More recent valleys may require local microenvironments to allow valley formation to occur rather than major alteration of the global climate.


Figure 1. Hartmann best fit ages for the 26 highland valley networks we consider; error bars incorporate both counting and the fit of isochrons to the data ($2\sigma$). See [4] for raw data.

Fig 2. (A) CTX image P04_002560_2309, showing glacial lobes and small incised valleys, and (B) interpretation.

Fig 3. CTX image P05_002791_1336 showing sinuous valleys on the ejecta of a 25-km crater.

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Table 1. Age boundaries computed in the Neukum and Hartmann isochron systems [12, 13], enforcing the Tanaka definitions [11] (in bold) for a specific cumulative number of craters in an area of $10^6$ km$^2$, larger than diameter X (N(X)).