The timing of martian valley network activity: Constraints from buffered crater counting

Caleb I. Fassett, James W. Head III *

Department of Geological Sciences, Brown University, Providence, RI 02912, USA

Received 30 July 2007; revised 21 October 2007
Available online 6 January 2008

Abstract

Valley networks, concentrations of dendritic channels that often suggest widespread pluvial and fluvial activity, have been cited as indicators that the climate of Mars differed significantly in the past from the present hyperarid cold desert conditions. Some researchers suggest that the change in climate was abrupt, while others favor a much more gradual transition. Thus, the precise timing of valley network formation is critical to understanding the climate history on Mars. We examine thirty valley network-incised regions on Mars, including both cratered upland valley networks and those outside the uplands, and apply a buffered crater counting technique to directly constrain when valley network formation occurred. The crater populations that we derive using this approach allow assessment of the timing of the last activity in a valley network independent of the mapping of specific geological units. From these measurements we find that valley networks cluster into two subdivisions in terms characteristics and age: (1) valley network activity in the cratered highlands has an average cessation age at the Noachian–Hesperian boundary and all valleys that we crater counted are Early Hesperian or older. No evidence is found for valley networks in the cratered uplands of Late Hesperian or Amazonian age. The timing of the cessation of cratered upland valley network activity at the Noachian–Hesperian boundary also corresponds to a decline in the intensity of large crater formation and degradation and to the apparent end of phyllosilicate-type weathering. (2) A few valley network-incised regions formed outside of the cratered uplands on volcanic edifices, in association with younger impact craters, and on the rim of Valles Marineris. We applied our buffered crater counting technique to four such valleys, on the volcanoes Ceraunius Tholus, Hecates Tholus, and Alba Patera and on the rim of Echus Chasma, and find that each has distinctive and different Late Hesperian or Early Amazonian ages, indicating that valley networks formed from time to time in the post-Noachian period. Unlike the cratered upland valley networks, these isolated occurrences are very local and have been interpreted to represent local conditions (e.g., snowpack melted during periods of intrusive volcanic activity). In contrast to a gradual cessation in the formation of valley networks proposed by some workers, our new buffered crater counting results indicate a relatively abrupt cessation in the formation of the widespread cratered upland valley networks at approximately the end of the Noachian, followed only by episodic and very localized valley network formation in later Mars history, very likely due to specific conditions (e.g., local magmatic heating). These valley network ages and correlations are thus consistent with a major change in the near-surface aqueous environment on Mars at approximately the Noachian–Hesperian boundary. The Noachian environment supported surface running water and fluvial erosion across Mars in the cratered uplands, enhanced crater degradation, and a weathering environment favoring the formation of phyllosilicates. The Hesperian–Amazonian environment was more similar to the hyperarid cold desert of today, with valley networks forming only extremely rarely and confined to localized special conditions. Sources of water for these latter occurrences are likely to be related to periodic mobilization and equatorward migration of polar volatiles due to variations in spin-axis orbital parameters, and to periodic catastrophic emergence of groundwater.

© 2008 Elsevier Inc. All rights reserved.

Keywords: Mars, surface; Geological processes; Cratering

1. Introduction and background

1.1. Introduction

Valley networks on Mars are branching erosional features generally thought to result from fluvial erosion of the sur-
face by water; two modes of occurrence are observed (Carr, 1996). Cratered highland valley networks occur predominantly in cratered highland terrain of Noachian age (the earliest period of martian history). Other valley networks, many fewer in number, occur at mid-to-higher latitudes on volcanic edifices, plateaus and in association with a few craters. Typical widths for valley network segments are ~1 km, although a few large valleys are as wide as ten kilometers (Carr, 1996; Williams and Phillips, 2001). Valleys have a median depth of about 80 m. Typical lengths are less than a few hundred kilometers; however, the longest valley network systems appear to have been integrated up to ~5000 km (e.g., the Naktong Vallis/Scamander Vallis/Mamers Vallis system) (Irwin et al., 2005a).

Valley network drainage densities are moderately lower than valley systems on Earth measured at a similar scale (Hynek and Phillips, 2003; Carr and Chuang, 1997). Valley networks appear to have had less influence on modifying the characteristics of drainage basin topography than is typical on Earth (Stepinski and Collier, 2004), and low-order tributaries appear less commonly on Mars than on Earth, suggesting a less mature drainage system on Mars. However, where small tributaries are observed, they commonly have source points near drainage divides (e.g., Irwin and Howard, 2002). The fact that valleys have distributed points of origin that are commonly found at or near drainage divides is strong evidence that precipitation occurred on Mars; groundwater seepage is unlikely to result in substantial erosion near drainage divides without a significant recharge mechanism (e.g., Carr, 1983; Goldspiel and Squyres, 1991; Gulick, 2001). An important role for precipitation in forming the valley networks is also suggested by the amount of fluid delivery required to achieve peak discharge rates inferred for valley networks based on scaling laws (Irwin et al., 2005b).

For these reasons, valley network formation is commonly thought to imply the presence of a different climate on early Mars from that of the hyperarid cold desert climate of today (e.g., Jakosky and Phillips, 2001). The type of climate conditions required to produce the observed geomorphology is more controversial, however. Arguments have been put forward for a spectrum of scenarios, from a warm, wet surface environment that commonly supported rainfall (Craddock and Howard, 2002), to a generally arid climate with intermittent surface wetting (Stepinski and Stepinski, 2005), to formation of valley networks under cold, dry conditions similar to the present environment on Mars (Gaidos and Marion, 2003).

Because of their potential importance as a climate signal, there has long been interest in determining the time of onset, duration and time of cessation of valley network formation. Most valley networks are found in the cratered upland terrain, which dates from the Noachian, and for this reason many investigators have interpreted them to have been active primarily in the Noachian, early in the history of Mars (e.g., Carr and Clow, 1981; Gulick and Baker, 1990). Others have argued for a more prolonged formation of cratered upland valley networks, extending into the Amazonian (Scott and Dohm, 1992; Scott et al., 1995). Valley networks found outside the cratered uplands, such as those on some of the Tharsis volcanoes (Gulick and Baker, 1990), have been found by many to be younger than the Noachian cratered upland valley networks, and are interpreted by some to have formed in association with post-Noachian climate excursions, perhaps triggered by outflow events and the emplacement of a northern lowlands ocean (e.g., Baker et al., 1991; Baker, 2001). On the other hand, Craddock and Howard (2002) argued that there is “no discontinuity between the ages of highland valley networks and those found on the Tharsis volcanoes,” and concluded that “[t]he geologic record does, in fact, support continued erosion and modification in the martian highlands throughout the early history of Mars, implying a long-lived episode of valley network formation whose rate diminished through a gradual climate change.” Thus, in this interpretation, environmental conditions allowing valley network activity across Mars may have persisted well into the Hesperian or Amazonian periods, although at diminishing rates. Our aim in this study is to use counts of impact craters superposed on valley networks to develop constraints on: (1) whether the two populations of valley networks differ substantially in age, or whether they formed continuously, (2) whether any transition in valley network formation on Mars was gradual or more step-like in nature, and (3) whether the distribution of ages and comparison to other geological events and processes might provide information about the causative processes for valley network formation.

1.2. Prior studies on the timing of martian valley network formation

Candidate fluvial features on Mars include valley networks, outflow channels, and gullies and analysis of these fluvial features has been a fundamental aspect of understanding the geological history of Mars. Much of the initial work (e.g., Malin, 1976; Masursky et al., 1977) focused on the ages of the largest fluvial valleys, which are generally classified as outflow channels. Constraining the formation ages of the smaller, integrated valley network systems is more difficult, largely because of the much smaller surface area (poor counting statistics) and the often-ambiguous stratigraphic relationships between valleys and surrounding geological units. Many investigators have treated this problem in detail since the Mariner era including Pieri (1976, 1980a, 1980b), Carr and Clow (1981), Baker and Partridge (1986), Scott and Dohm (1992), Craddock and Maxwell (1993), Maxwell and Craddock (1995), Carr (1995), and Scott et al. (1995).

Using crater counts on high-resolution Viking data, Pieri (1980a, 1980b) employed two approaches to derive age constraints for five valleys in the highlands. First, he determined the number of superposed crater directly on these valley networks (178 superposed craters; only 11 of which were greater than ~4 km) (Pieri, 1980b). Together with the measured surface area, this allowed him to derive a crater density that implies a Late Noachian age [with \( N(5) \sim 320 \pm 100 \), see Tables 1 and 2]. Note that throughout this paper we follow the standard convention that \( N(X) \) is the cumulative number of craters of size greater than or equal to diameter \( X \) normalized to an
The timing of valley network formation on Mars

The area of $10^6$ km$^2$; such a value acts as a summary statistic with reference to a specific diameter, easing comparison between different measurements (and period boundaries; see Tables 1 and 2). However, this single number carries less information than detailed than comparison of measured size–frequency distributions as a whole.

The second approach utilized by Pieri (1980a, 1980b) was to determine the position of the “valley network-incised” surface unit in the context of the global stratigraphy of Mars by looking at the crater population of the areas that surround the valleys. This expands the surface area being considered, and thus helps avoid some of the statistical limitations resulting from the small surface area of the valleys themselves. Superposition of the valley on the dated surface requires that the age of the unit dissected by the valley network is an upper bound on the time that the valley on the dated surface requires that the age of the unit dissected by the valley network is an upper bound on the time on the valley on the dated surface requires that the age of the unit dissected by the valley network is an upper bound on the time that the valley on the dated surface requires that the age of the unit dissected by the valley network is an upper bound on the time that the valley on the dated surface requires that the age of the unit dissected by the valley network is an upper bound on the time.

Using this technique, Pieri (1980b) found a Mid-Noachian age for the valley network-incised highlands [from the data in his Fig. 33, $N(5) \sim 540$ and $N(16) \sim 160$ (84 craters larger than 4 km)] (see Tables 1 and 2).

However, the cumulative size–frequency distribution observed by Pieri (1980b) on units cut by valley networks has a lower power-law slope than what would be expected from a production function consistent with the larger craters alone. This shallow slope is commonly observed in the highlands; it is usually inferred to imply preferential removal of small craters in the highlands by erosion and gradation during the Noachian (e.g., Chapman and Jones, 1977; Carr and Clow, 1981; see also Fassett and Head, 2007a). Preferential small-crater removal makes the interpretation of the crater size–frequency distribution as a simple age-dependent accumulation difficult, and thus complicates the determination of actual formation age in ancient terrains.

Other workers have also attempted to determine the crater population of dissected highlands units surrounding valleys. Carr and Clow (1981) used Viking data to survey the highlands from $65^\circ$ S to $65^\circ$ N. They observed similar crater populations in both dissected and undissected heavily-cratered highlands plateau material, with $N(5)$ of $\sim 380$ and $N(16)$ of $\sim 110$, implying a Mid-to-Late Noachian age (see Tables 1 and 2). These results are qualitatively similar to, and consistent with, the populations found by Pieri (1980a, 1980b) and imply that valley networks were active during the Late Noachian.

When examining the units on which the valleys have been incised to determine an upper age limit of incision, one cannot interpret the derived surface age as representing the period of valley incision itself; instead, valleys must only be younger than the surfaces they incise. Furthermore, the fact that valleys are predominantly found on Noachian highlands terrain does not necessarily imply that they are themselves Noachian in age. An alternative hypothesis considered by Carr and Clow (1981) is that geological factors, such as erodability or availability of groundwater, might have concentrated the location of valley networks in the heavily cratered Noachian highlands even if their activity occurred after some unincised units were deposited. However, Carr and Clow (1981) argue that this scenario is unlikely, because valley formation appears to have required recharge and a hydrological cycle. Since the most plausible recharge mechanisms would not be focused on the highlands alone, Carr and Clow (1981) concluded that the simplest scenario is that the vast majority of valley networks (>99%) are in fact old (Late Noachian or older).

To summarize, the work of both Pieri (1980a, 1980b) and Carr and Clow (1981) suggests that most valley networks are old and very likely Noachian in age. This conclusion is based on: (1) the recognition that valleys must be younger than the Mid-Late Noachian-aged cratered highlands that they erode; (2) the fact that valley networks are largely absent on units younger than the Noachian and are predominantly found in the heavily cratered highlands (Pieri, 1976; Carr and Clow, 1981); (3) the observation that valleys appear to be older than the ridged plains, which are generally Hesperian in age (Pieri, 1976; Tanaka, 1986; Carr, 1996) (Fig. 1). These factors argue that the formation of virtually all cratered upland small valley network formation ceased by the end of the Noachian or the earliest Hesperian.

Several workers have employed a different technique to determine the age of valley networks. These studies com-
Fig. 1. Examples of stratigraphic boundaries between dissected terrains and other highland units. Ridged and smooth plain units, such as the Hesperian ridged plains (HR) are common throughout the highlands and often preferentially fill regions of low-lying topography such as basin or crater floors. The dashed lines are the boundaries between Noachian and Hesperian units, as mapped at the 1:15 million scale by Scott and Tanaka (1986) or Greeley and Guest (1987). This illustrates the potential pitfalls in using the stratigraphic method for constraining valley activity at this scale of mapping alone. Valleys can be embayed by young er units, small regions of smooth material (possible younger plains unit) are not mapped, and unit boundaries determined at this broad scale may be too generalized to determine local relationships. Locations are (A) 61° E, −13° N, (B) 14.5° E, −6.5° N, (C) 71° E, −23° N, (D) 148° E, −17° N.

pared fluvial features with units mapped on the surface of Mars (Scott and Dohm, 1992; Scott et al., 1995; Carr, 1995; Harrison and Grimm, 2005) using global Mars mapping at the 1:15,000,000 scale (Scott and Tanaka, 1986; Greeley and Guest, 1987). Stratigraphic principles require that a valley be no older than the surface that it incises; thus, if a valley network crosses a known Late Noachian-aged unit, it must be Late Noachian or younger. Using this technique, combined with valley appearance and crater counts on basin floor material, Scott et al. (1995) estimated that >25% (perhaps as high as 35%) of highland valley networks on Mars are younger than the Noachian. However, Carr (1995) examined 827 valley networks and the units they
incise and argued that only 8% are likely to be younger than the Noachian.

The differences between the ages derived by Carr (1995) and Scott et al. (1995) are striking, especially since they utilize the same techniques. However, the cause of this discrepancy can be understood if one considers the difficulties that can arise when mapping units, especially at the 1:15,000,000 scale (see discussion in Carr, 1996). For example, this stratigraphic approach requires (1) accurate classification of valleys and distinguishing them from outflow channels, which appear to be formed by a different process, (2) complete and exact knowledge of unit boundaries, (3) detailed understanding of the relationships of valleys with their surrounding, and underlying, geological units (embayment versus incision), and (4) accurate age assessments of all relevant units. Each of these tasks requires time-consuming and difficult procedures, and unit boundaries and embayment relationships are often transitional and imprecise. The most robust constraint available to determine the ages of individual units is their population of superposed craters. Such superposed populations can be difficult to assess for small and irregularly shaped units or features such as the valley networks. Unit boundaries and stratigraphic relationships (for example, Hesperian lava flows emaying valley network-incised terrain; Fig. 1) can also be very difficult to ascertain precisely due to low-resolution image data, data obtained with poor illumination conditions for mapping, transitional contacts, and/or superposed surficial units (dunes and mantles) obscuring key contact locations.

The types of difficulties inherent in this stratigraphic technique are part of the motivation for our present study. We developed a methodology that derives an age for valley activity using only the relationship of the valley system with impact craters, rather than relying on stratigraphic relationships between units mapped at low-resolution. The advantages of this approach have been recognized before. For example, Baker and Partridge (1986) used craters directly superposed on valleys to determine when the valleys were active. They approached the determination of the age of these networks using three methodologies: (1) They apply a “conservative” method, where they include only craters superposed directly on the valley floor or burying the valley were included. Their count area is only the area of the valley network itself. (2) The “perimeter-crater” method, where any crater with a clear superposition relationship with the valley was included, including the case in which the crater ejecta cross-cuts the valley. The sampling area was then defined as the valley network area plus the area within a distance of 1 km around the rim of any included crater. (3) The “crater-fraction” method, which excluded craters on interfluvies and only included in the count the fraction of large craters that fell within the valley itself. In this case, the sampling area was taken as the valley network, as was the case with their conservative method.

Baker and Partridge (1986) argue that the perimeter-crater method may give the best sense of the age of the valley networks. Their preferred “perimeter” methodology yields values of $N(5) = 410$ (pristine networks), and $N(5) = 500$ (degraded networks) (interpolated from their Table 2), suggesting that valleys were generally Noachian in age (see Tables 1 and 2). As Baker and Partridge (1986) point out, however, a key difficulty in applying each of these techniques arises from the definition of the count area. For example, their “perimeter crater” method appears to underestimate the relevant sampling area of a crater count because it only includes where craters are actually superposed on a valley, plus an arbitrary one-kilometer buffer around the crater rim. This excludes the area around a valley where a crater, if it had formed, would have been superposed on the valley and included in the count; this latter situation is the case that our buffering technique calculates (see Section 2.2). This “perimeter” methodology leads to an estimate for the count area that is too small at all crater sizes. This issue is exacerbated at large crater diameters, since larger craters may impact over a larger area and remain superposed on the valley, a factor that decreases the measured power-law slope for the crater size–frequency distribution. It also causes the cumulative number of craters at $N(5)$ to be overestimated more than the cumulative number at smaller sizes, such as $N(2)$.

A final independent method that has been utilized to constrain when fluvial activity occurred on the martian highlands is to examine the fresh crater population and compare it with the highlands population as a whole (Craddock and Maxwell, 1993; Maxwell and Craddock, 1995). Craddock and Maxwell (1993) argue that degradation of craters in the highlands of Mars was dominated by fluvial erosion and degradation in the Noachian. From this they reason that a measurement of when a stable, fresh and essentially undegraded population began to develop should provide an age estimate of when fluvial erosion and degradation processes ceased. Measurements of the fresh crater population of the dissected highlands yield an age of $N(5) = 188$ to 251, in a narrow range around the Noachian/Hesperian boundary as defined by Tanaka (1986), at $N(5) = 200$ (Tables 1 and 2) (Craddock and Maxwell, 1993; Maxwell and Craddock, 1995). We discuss these prior results in comparison with our new results in Section 4.

In summary, despite many advances in the assessment and understanding of the chronology and timing of valley networks, imprecision and uncertainty remain. To try to improve our understanding of valley network chronology, in this study we have used a range of newly available data (to improve the quality of valley network and crater mapping) and a different approach (buffered crater counting) to reexamine this problem.

2. Methodology

2.1. Count regions and data

We mapped valleys and made crater counts using the buffered crater counting technique in thirty individual valley networks or valley-incised regions representing both the upland cratered terrain population (26) and those that occur outside this area (4). The valleys are areally representative of the populations (Fig. 2) and were chosen on the basis of past work on valley networks and availability of new high-resolution
Valleys outside the region from $-30^\circ$ to $30^\circ$ N latitude were generally not included in order to avoid the complicating effects of recent mantling material (Soderblom et al., 1973; Kreslavsky and Head, 2000; Mustard et al., 2001) and terrain softening (Squyres and Carr, 1986). The valley networks we map appear to represent $\sim 15$–20% of the total population of valley networks based on length. Our mapping of both valleys and superposed craters relied on a variety of available new and existing data, including the THEMIS IR global mosaic (Christensen et al., 2004), Viking MDIM 2.1 (Archinal et al., 2003) (both of which are $\sim 230$ m/pixel), MOLA gridded topography (e.g., Smith et al., 1999) ($\sim 460$ m/pixel), and HRSC image data (Neukum et al., 2004) (where available, up to 12.5 m/pixel). For each crater-count area, all the available data were included in a database in the ArcMap GIS environment for mapping of valleys and crater measurements. In all cases, the minimum crater size we used in our analysis was $>9$ pixels (linear dimension) in at least one of the available image datasets. As a result of this conservative recognition requirement, and because the craters we rely upon are typically $>2$ km in diameter, the effects of variable image resolution and quality are minimized and we did not observe a resolution rollover in any of our data.

2.2. Buffered crater counting

A variety of techniques for counting craters along linear or curvilinear features on planetary surfaces have been utilized in the past (e.g., Tanaka, 1982; Wichman and Schultz, 1989; Namiki and Solomon, 1994). As in these earlier studies, our approach takes advantage of the fact that large craters subtend more surface area than small ones, so that the effective count area (a buffer around the feature) is a function of the crater diameter under consideration (Fig. 3). The buffer we use includes all the area within a distance of the center of the valley of $S_{\text{buffer}} = 1.5D + 0.5W_v$ (on each side of the valley), where $W_v$ is the valley width and $D$ is the crater diameter under consideration. Thus, for a linear segment of a valley of length $L$, for crater diameter $D$, the total area included is $A(D) = 2LS_{\text{buffer}} = (3D + W_v)L$. The valley width/floor itself is usually a minor contributor to the buffer area, as $W_v$ is typically much less than $3D$ for the crater sizes we consider.

When examining the craters that fall within this buffer, a stratigraphic judgment is required to determine whether or not the crater is superposed on the valley. Fortunately, craters and their ejecta commonly alter the nature and topography of their surroundings sufficiently to make stratigraphic determinations possible. We know that any topography related to the crater that is superposed on a valley (e.g., its rim or ejecta) must have formed after valley activity ceased. If crater formation had occurred earlier, portions of the crater would have been modified or eroded away by later valley activity, or the topography would have caused the channel course to have altered. Because the buffered approach only includes craters that are stratigraphically superposed on the valley, the derived result should be a robust minimum age (lower limit) on the last activity in the valley.

Our buffer distance ($S_{\text{buffer}}$) is based on the assumption that it is possible to determine stratigraphic relationships for craters that have rims that fall within one crater diameter of the valley network. This is consistent with observations and expectations from scaling laws, which predict that the extent of continuous ejecta is $\sim 1D$ (Melosh, 1989). The assumption that we can determine stratigraphic relationships at distances of one crater diameter beyond the crater rim is the primary difference between our approach and earlier linear counting approaches. In these earlier approaches (Tanaka, 1982; Wichman and Schultz, 1989), only craters whose rims would directly superpose the dated feature were included. To test whether or not our assumption is reasonable, we compiled an analysis using the more stringent buffer definition of Tanaka (1982) and Wichman and Schultz (1989) and compared it to the results from our buffered technique for the same areas. The crater-size frequencies derived using the more stringent buffer are consistent with what we observe using the broader buffer;
in other words, there are no apparent systematic errors resulting from our choice of a buffer size.

Our procedures for the count are as follows: (1) We first map the valley system being examined and determine its average width. (2) We then find all craters clearly superposed upon the valley that have a center within the buffer area appropriate for the specific crater diameter (so that its rim falls within a distance of one crater diameter of the valley). (3) A count area is then computed at each crater size by repeatedly applying the ArcMap buffer function of the appropriate size to the mapped valleys (as illustrated schematically in Fig. 3). Arcmap computes a buffer by expanding the area around a mapped feature for a distance specified (for our purposes specified using the equation for $S_{\text{buffer}}$, given above), and combines regions where the buffer around segments overlap. Finally, to avoid any distortion as a result of geographic projection, we always compute this buffer area in an appropriate local map projection.

2.3. Age and period determination

The results of the buffered crater counting approach are presented in a manner similar to what is derived using the more common areal counting method: a frequency of craters of specified size per unit area. These data can be analyzed either as (1) a cumulative frequency of craters greater than or equal to some size, or (2) using incremental frequencies within a fixed range of diameters (see, e.g., Crater Analysis Techniques Working Group, 1979). From these frequencies, it is possible to (1) assign valley activity to a stratigraphic period in the history of Mars, (2) determine relative ages with other surface features for which counts exist, and (3) determine absolute ages, assuming a production function/production rate for Mars.

When we derive absolute ages in this contribution, we have chosen to apply two commonly used production functions: the Neukum production function (Neukum and Ivanov, 2001; Ivanov, 2001; see also Werner, 2005), and the 2004 iteration of the Hartmann production function (Hartmann, 2005). Following the long-standing conventions of these workers, we apply the Hartmann production function to data in the incremental format and the Neukum production function to cumulative data (see Appendix A).

Lack of knowledge of the exact historical impact crater production rate on Mars leads to a systematic uncertainty in absolute ages of up to a factor of $\sim 2-4$, and the degree of uncertainty depends on the age of terrain being considered (e.g., Hartmann and Neukum, 2001). Along with this systematic uncertainty, there are also non-negligible differences in the ages that are derived using the Hartmann and Neukum production functions. For example, calculating the age of Noachian/Hesperian boundary in the Neukum system using the Tanaka (1986) cumulative frequency boundaries at $N(5)$ gives a best-fit age of $\sim 3.74$ Gyr, whereas in the Hartmann system this falls at $\sim 3.55$ Gyr (see Tables 1 and 2 and Appendix A). Thus, where we quote absolute ages in this paper, we always reference them to a specific system. However, it is worth noting that the crater frequencies that we use for the stratigraphic boundaries are based on the Tanaka (1986) definition using $N(2)$, $N(5)$, and $N(16)$ for both the Hartmann and Neukum production functions (see Tables 1 and 2 and discussion in Appendix A). Therefore, a valley that is determined to have been active up to the Late Noachian in the Hartmann system typically, but not always, is assigned a Late Noachian in the Neukum system as well. In both the Hartmann and Neukum systems, we determine absolute ages using a least-squares method (see Appendix B). Any new information causing a reassessment of the production function would only serve to shift the derived absolute ages and should have minimal effect on the relative chronology or assignment to a specific geologic period.

3. Results

Counts were completed for the thirty valley systems shown in Fig. 2. Incremental and cumulative crater size–frequency diagrams for each of these systems are given in Fig. 9. Using these measured size–frequency distributions, we have calculated absolute ages for each of the thirty examples in the Hartmann and Neukum systems to assess when the latest period of valley activity occurred; a summary of these results is shown in Table 3 and Fig. 4. In this section, we describe in detail and compare two examples: Vichada Vallis, a valley network in the heavily-cratered highlands, and valleys on the high-latitude vol-
The period of activity in Vichada Vallis is not well constrained by stratigraphy alone. An upper limit for the age of the present valley system is the Hellas impact basin event, because Vichada Vallis is superposed on the basin rim. Furthermore, the valley network drainage basin is strongly influenced by Hellas topography, which established its regional slope and base level. Constraining the age of Hellas formation itself is a challenging problem, because much of its interior and surroundings have been deeply modified by post-impact processes. Furthermore, the large basins on Mars may have formed during a period of Late Heavy Bombardment between 3.8 and 4.0 Gyr which may make establishing firm dates for this period from crater statistics alone impossible (e.g., Solomon and Head, 2007). Nonetheless, Werner (2005) argues that the Hellas basin-forming event dates to 3.99 Gyr \( [N(5) = 895, N(16) = 230] \) in the Neukum system, which would date it to the end of the Early Noachian. This thus marks an upper limit for the formation of Vichada Vallis. Near its southern limit, Vichada Vallis appears embayed by smooth plains that are interpreted as Hesperian ridged plains (Hr). Such an embayment relationship would indicate that Vichada Vallis is older than the ridged plains, and formed during or prior to the Early Hesperian. This type of embayment relationship between valley networks and ridged plains material is common throughout the highlands.

### Table 3

<table>
<thead>
<tr>
<th>#</th>
<th>Valley system</th>
<th>Number of craters ( D = 2 ) to 32 km</th>
<th>Total VN length (km)</th>
<th>( N(5) ) Neukum best fit</th>
<th>( N(5) ) Hartmann best fit</th>
<th>Neukum age</th>
<th>Hartmann age</th>
<th>Neukum period</th>
<th>Hartmann period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Licus Vallis</td>
<td>7</td>
<td>419</td>
<td>334</td>
<td>442</td>
<td>3.83</td>
<td>3.73</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>2</td>
<td>123E, 0N</td>
<td>5</td>
<td>239</td>
<td>594</td>
<td>540</td>
<td>3.93</td>
<td>3.77</td>
<td>MN</td>
<td>LN</td>
</tr>
<tr>
<td>3</td>
<td>131E, −5N</td>
<td>16</td>
<td>1493</td>
<td>202</td>
<td>172</td>
<td>3.74</td>
<td>3.5</td>
<td>LN</td>
<td>EH</td>
</tr>
<tr>
<td>4</td>
<td>155E, −12.5N</td>
<td>17</td>
<td>1841</td>
<td>172</td>
<td>168</td>
<td>3.72</td>
<td>3.5</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>5</td>
<td>Al-Qahira Vallis</td>
<td>27</td>
<td>1388</td>
<td>393</td>
<td>393</td>
<td>3.86</td>
<td>3.71</td>
<td>MN</td>
<td>LN</td>
</tr>
<tr>
<td>6</td>
<td>Evros Vallis</td>
<td>16</td>
<td>1559</td>
<td>219</td>
<td>260</td>
<td>3.76</td>
<td>3.62</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>7</td>
<td>Meridiani: 0E, −5N</td>
<td>15</td>
<td>1447</td>
<td>165</td>
<td>194</td>
<td>3.71</td>
<td>3.54</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>8</td>
<td>−9E, −5N</td>
<td>10</td>
<td>846</td>
<td>262</td>
<td>323</td>
<td>3.79</td>
<td>3.67</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>9</td>
<td>5E, −17N</td>
<td>19</td>
<td>941</td>
<td>368</td>
<td>350</td>
<td>3.85</td>
<td>3.69</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>10</td>
<td>Naro Vallis</td>
<td>14</td>
<td>843</td>
<td>517</td>
<td>663</td>
<td>3.90</td>
<td>3.81</td>
<td>MN</td>
<td>LN</td>
</tr>
<tr>
<td>11</td>
<td>Parana and others</td>
<td>84</td>
<td>8627</td>
<td>188</td>
<td>163</td>
<td>3.73</td>
<td>3.49</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>12</td>
<td>−13E, −7N</td>
<td>16</td>
<td>1476</td>
<td>253</td>
<td>252</td>
<td>3.79</td>
<td>3.61</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>13</td>
<td>−7E, −16N</td>
<td>7</td>
<td>398</td>
<td>357</td>
<td>331</td>
<td>3.85</td>
<td>3.67</td>
<td>MN</td>
<td>LN</td>
</tr>
<tr>
<td>14</td>
<td>Vichada Vallis</td>
<td>55</td>
<td>4450</td>
<td>268</td>
<td>296</td>
<td>3.80</td>
<td>3.65</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>15</td>
<td>77 E, 18 N</td>
<td>7</td>
<td>231</td>
<td>323</td>
<td>454</td>
<td>3.83</td>
<td>3.74</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>16</td>
<td>Naktong and others</td>
<td>76</td>
<td>7992</td>
<td>155</td>
<td>169</td>
<td>3.69</td>
<td>3.5</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>17</td>
<td>62.5E, −16N</td>
<td>35</td>
<td>4534</td>
<td>203</td>
<td>219</td>
<td>3.75</td>
<td>3.58</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>18</td>
<td>Tagus and others</td>
<td>42</td>
<td>3603</td>
<td>197</td>
<td>209</td>
<td>3.74</td>
<td>3.56</td>
<td>EH</td>
<td>LN</td>
</tr>
<tr>
<td>19</td>
<td>132.5E, −22N</td>
<td>28</td>
<td>3444</td>
<td>158</td>
<td>149</td>
<td>3.70</td>
<td>3.45</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>20</td>
<td>−9E, −11N</td>
<td>42</td>
<td>3740</td>
<td>193</td>
<td>193</td>
<td>3.74</td>
<td>3.54</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>21</td>
<td>Brazos and others</td>
<td>42</td>
<td>4852</td>
<td>167</td>
<td>151</td>
<td>3.71</td>
<td>3.46</td>
<td>EH</td>
<td>EH</td>
</tr>
<tr>
<td>22</td>
<td>65E, −9N</td>
<td>17</td>
<td>1495</td>
<td>297</td>
<td>257</td>
<td>3.81</td>
<td>3.62</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>23</td>
<td>Cusus Vallis</td>
<td>54</td>
<td>4924</td>
<td>289</td>
<td>261</td>
<td>3.81</td>
<td>3.62</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>24</td>
<td>−162E, −11N</td>
<td>24</td>
<td>1773</td>
<td>262</td>
<td>265</td>
<td>3.79</td>
<td>3.63</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>25</td>
<td>Warrego Valles</td>
<td>23</td>
<td>3294</td>
<td>225</td>
<td>257</td>
<td>3.77</td>
<td>3.62</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>26</td>
<td>Nanedi and others</td>
<td>29</td>
<td>5716</td>
<td>240</td>
<td>226</td>
<td>3.78</td>
<td>3.59</td>
<td>LN</td>
<td>LN</td>
</tr>
<tr>
<td>27</td>
<td>Hecates Tholus</td>
<td>14*</td>
<td>3939</td>
<td>72</td>
<td>61</td>
<td>3.50</td>
<td>2.06</td>
<td>EA</td>
<td>EA</td>
</tr>
<tr>
<td>28</td>
<td>Ceranuus Tholus</td>
<td>12*</td>
<td>2652</td>
<td>85</td>
<td>89</td>
<td>3.55</td>
<td>2.96</td>
<td>LH</td>
<td>LH</td>
</tr>
<tr>
<td>29</td>
<td>VM/Echus Plateau</td>
<td>5*</td>
<td>1322</td>
<td>47</td>
<td>59</td>
<td>3.27</td>
<td>1.98</td>
<td>EA</td>
<td>EA</td>
</tr>
<tr>
<td>30</td>
<td>Alba Patera</td>
<td>23</td>
<td>11,831</td>
<td>76</td>
<td>52</td>
<td>3.52</td>
<td>1.74</td>
<td>EA</td>
<td>EA</td>
</tr>
</tbody>
</table>

* For Hecates, Ceraunius, and Echus, analysis included craters down to 1 km.

Vichada Vallis is a highland valley network draining a region northeast of Hellas basin that has been mapped as Noachian dissected terrain \( (Npdl) \) (Greeley and Guest, 1987) \( (Fig. 5A)\). It has a dendritic planform with numerous tributaries, many of which head at drainage divides. These drainage divides are commonly controlled by pre-existing large impact craters such as Millochau crater \( (Fig. 5A)\). The average slope of the Vichada drainage basin is 0.4% and valley segments are commonly well-incised \( (∼150–200 \text{ m depth}) \) and wide \( (∼2 \text{ km width}) \) \( (Fig. 5C)\). These widths and depths are typical for valley networks on Mars, though slightly larger than median values \( (Williams and Phillips, 2001) \).

The period of activity in Vichada Vallis is not well constrained by stratigraphy alone. An upper limit for the age of the present valley system is the Hellas impact basin event, because Vichada Vallis is superposed on the basin rim. Furthermore, the valley network drainage basin is strongly influenced by Hellas topography, which established its regional slope and base level. Constraining the age of Hellas formation itself is a challenging problem, because much of its interior and surroundings have been deeply modified by post-impact processes. Furthermore, the large basins on Mars may have formed during a period of Late Heavy Bombardment between 3.8 and 4.0 Gyr which may make establishing firm dates for this period from crater statistics alone impossible \( (e.g., Solomon and Head, 2007) \). Nonetheless, Werner (2005) argues that the Hellas basin-forming event dates to 3.99 Gyr \( [N(5) = 895, N(16) = 230] \) in the Neukum system, which would date it to the end of the Early Noachian. This thus marks an upper limit for the formation of Vichada Vallis. Near its southern limit, Vichada Vallis appears embayed by smooth plains that are interpreted as Hesperian ridged plains \( (Hr) \). Such an embayment relationship would indicate that Vichada Vallis is older than the ridged plains, and formed during or prior to the Early Hesperian. This type of embayment relationship between valley networks and ridged plains material is common throughout the highlands \( (Fig. 1) \).
The timing of valley network formation on Mars

Fig. 4. (A) A summary of all ages determined for the valley systems in the Hartmann age system (see also Table 3). The ‘classic’ highland valley networks have ages concentrated at approximately the Noachian/Hesperian boundary. Error bars are the 2-sigma range, and are a combination of two elements: uncertainty of the fit for the best-fit isochron and Poisson counting statistics (see Appendix A). The large error bars for the younger features are primarily a result of the downturn in the modeled cratering rate by the Hesperian. For example, in the Hartmann system, there is a greater difference in crater density between surfaces that are 3.7 Gyr old and 3.6 Gyr old than those that are 3 and 2 Gyr due to this decline (e.g., Hartmann, 2005). Uncertainties shown here do not include inherent uncertainty in the absolute calibration of the Hartmann age system or in the location of the period boundaries in the Hartmann system (see Appendix A). Changes in the absolute calibration will have no effect on the relative age determinations and should not alter the main conclusions of this study. (B) Ages of thirty valleys on Mars; yellow features (outlined in black) are Early Hesperian or older and features in red (outlined in white) have Late Hesperian or Early Amazonian ages (see Table 3). Basemap is MOLA altimetry shaded relief, 50° S to 50° N (Mercator). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Noachian, with an absolute age of 3.65 Gyr in the Hartmann system, 3.80 Gyr in the Neukum system (Figs. 5E and 5F). The Vichada Vallis crater count has particularly robust counting statistics, with 55 craters between 2 and 32 km, and the range of uncertainty is entirely confined to the Late Noachian (Fig. 4). Reference to Fig. 4 shows that all other cratered upland valley networks have comparable ages, with a mean age at the Noachian–Hesperian boundary.
Fig. 5. Example valley network count areas with valleys (thin black lines) and superposed craters (circles). (A) Vichada Vallis THEMIS IR mosaic. (B) Alba Patera THEMIS IR mosaic. (C) Inset of Vichada Vallis THEMIS IR mosaic (shown in dotted line in frame A). Note the width and depth of valley incision, both of which are greater than the valleys on Alba Patera. This inset also shows the relationships of the valley with craters; the two largest craters are both counted, one because it clearly impacted directly into the valley, and the other because its ejecta cuts across a valley segment. (D) Inset of Alba Patera valleys (shown in dotted line in frame B) from HRSC orbit 2895. Note how much smaller and denser the valleys on Alba Patera are than those of Vichada Vallis. The graben in this image clearly post-dates valley formation and is thus a stratigraphic constraint. The ~5 km crater in the center of the image also clearly post-dates the valley, as its ejecta superpose multiple valley segments. (E) Cumulative size–frequency distributions of Vichada Vallis (black circles) and Alba valleys (white circles), with Neukum isochrons (Neukum and Ivanov, 2001). (F) Incremental size–frequency distributions of Vichada Vallis (black circles) and Alba valleys (white circles), with Hartmann (2005) iteration isochrons (Hartmann, 2005). The observed crater populations suggest that Vichada Vallis is Late Noachian in age and the valleys on Alba Patera are early Amazonian in age. Note that since the valleys on Alba have a factor of ~4 less craters per square kilometer than Vichada Vallis, we can say with great statistical confidence ($p \sim 0.0001$) that they are of different age (see text).
3.2. Outside the cratered uplands example: valleys on Alba Patera

Alba Patera is a well-studied, low-relief shield at the margins of the Tharsis rise and northern lowlands (e.g., Ivanov and Head, 2006). It is situated at northern mid-latitudes (Fig. 2), well away from the cratered uplands where the majority of valley networks occur. The extensive valleys that incise the north flank of Alba Patera have an unusually high drainage density (Gulick and Baker, 1989) and the integrated length of the valleys on its surface are among the greatest for any incised location on Mars (Fig. 5B). The density of valleys on Alba Patera has led to the suggestion that the surface they erode was relatively friable, perhaps formed by runoff and erosion of an impermeable ash mantling layer (Gulick and Baker, 1989). Alternatively, the surface mantle may be a dust and ice mantling unit, and melting of this unit itself may have been the source of water to form the Alba valleys (Ivanov and Head, 2006). Morphometrically, the valleys on Alba are somewhat smaller than valley networks in the cratered uplands, such as Vichada Vallis. Valley segments are typically ~500 m wide and ~50 m deep (Fig. 5D). The average slope of the north flank of Alba is ~0.2%.

Based on stratigraphic constraints, the valleys on Alba Patera have long been considered to be younger than their cratered upland counterparts (see Gulick and Baker, 1989). Valleys on the north flank of Alba incise lava flows mapped as Early Amazonian in age (Scott and Tanaka, 1986). These valleys are cut by a system of graben thought to have developed later in the Early or Mid-Amazonian (Fig. 5D; see also Ivanov and Head, 2006). Thus, the valley networks at Alba Patera are stratigraphically much younger than those in the cratered uplands. Given these unusually strong stratigraphic age constraints, the Alba Patera valley network system also provides an excellent test of our crater counting methodology.

Because Alba Patera has such extensive valley networks and such a sizeable total network length, our buffered crater count approach samples a large area, and thus has robust counting statistics. On the basis of our analysis, we find an Early Amazonian age for the Alba Patera valley systems, with best fit ages of 1.74 Gyr (Hartmann system) or 3.52 Gyr (in the Neukum system) (Figs. 5E and 5F). This age derived from our buffered crater-counting approach is consistent with the stratigraphic constraints described previously. The buffered crater counting technique we utilize in our analyses is independent of this stratigraphy, and thus the similar results help to verify our methodology and the ages derived from our analyses.

How does the Alba Patera buffered crater count compare with the population that is superposed on Vichada Vallis (Figs. 5E and 5F)? Alba Patera has approximately a third of the crater density of this highland example and thus these populations are different with very high statistical confidence ($p$-value = 0.0001). Our data strongly indicate that in the case of Alba Patera, and a few other regions outside the cratered uplands, valley networks formed at a much younger time than valley networks such as Vichada Vallis in the cratered uplands. We discuss this more extensively in the following two subsections.

3.3. Summary: cratered upland valley networks

As typified by Vichada Vallis, most valleys we examined in the cratered uplands of Mars date to the end of the Noachian (Table 3, Fig. 4). The mean age of the twenty-six cratered upland examples is 3.53 Gyr (Hartmann system), or 3.75 Gyr (Neukum system), almost exactly at the Noachian–Hesperian...
Fig. 6. Crater size–frequency distributions of all our valley network buffered counts in the highlands aggregated as one count shown on a cumulative size–frequency diagram with Neukum production function-defined isochrons (A) and on an incremental size–frequency diagram using Hartmann isochrons (B). The agreement of the data and isochrons is quite strong.

boundary (Fig. 4). The earlier interpretation (Scott et al., 1995) that valley networks incised units younger than Early Hesperian in age may have resulted from either (1) the difficulty in precisely locating unit boundaries (especially using earlier, low-resolution data), or (2) that valleys may have been partly visible through thin embaying superposed later units.

In our analysis, we found that cratered upland valley networks are characterized by superposed impact crater populations consistent with individual valley network activity having ended in the Late Noachian to Early Hesperian (Fig. 4). There are two primary ways of interpreting these specific ages: (1) as an ensemble, where the variation between observations of different networks is statistical and not specifically reflective of the timing of the process, or (2) as a series of independent measurements, where each age represents an actual difference in the time that an individual valley ceased forming.

In the ensemble scenario, cratered upland valley network formation ended at the same point in time throughout the highlands. This scenario is plausible, since the valley network ages can be viewed as essentially coeval, given the overlapping uncertainty ranges for each measurement (see Fig. 4). Additionally, this approach allows aggregation of the valleys into a single count, which greatly improves counting statistics compared to the individual counts. When we aggregate the data in this manner, the resulting crater-size frequency distributions are shown in Fig. 6. The ages that are derived are 3.75 Gyr (Neukum system) \[ N(5)_N = 214 \] and 3.53 Gyr (Hartmann system) \[ N(5)_H = 187 \], essentially at the Noachian–Hesperian boundary (see Tables 1 and 2). The form of the crater-size frequency distribution for this aggregated data compares very well with model isochrons (Fig. 6).

An alternative view is that the variability in the derived best-fit ages (Fig. 4) may reflect real differences in the cessation of valley network activity for individual valley networks. In this case, our data would imply that the majority of valleys ceased activity during the Late Noachian but a few cratered upland valley networks continued to be active into the Early Hesperian. In this view, valley network-forming conditions were maintained in some parts of the highlands longer than in others, potentially over a period likely lasting a few hundred million years.

An independent measurement of two portions of the same highland valley network in Arabia Terra has been made by Hoke and Hynek (2007), using a buffered crater counting technique equivalent to what we used in our study. The crater counts and ages they derive (both segments of the same valley network date to the Noachian) are consistent with ours. However, Hoke and Hynek (2007) chose to emphasize the difference between the ages they derive for the two segments of the same valley network system. Their interpretation implies multiple episodes of valley formation within a single valley system.

In our view, it is difficult to distinguish with a high degree of confidence between a scenario where there are some differences in the age of cessation of specific valleys and the ensemble interpretation, in which the cessation occurred contemporaneously. This is because such a distinction requires interpretation at the level of counting uncertainty for our derived crater populations (Fig. 4). The quality of the aggregate fit of the ensemble data to the isochrons (Fig. 6) leads us to favor the ensemble view as the simplest explanation for our global observations. However, further detailed analysis is needed to assess whether some ancient cratered upland valley networks, or some valley
The timing of valley network formation on Mars

Fig. 7. A comparison of our highland valley network aggregate populations with fresh crater populations derived by (A) Craddock and Maxwell (1993) and (B) Maxwell and Craddock (1995). The close agreement of these measurements suggests that intense crater degradation declined at approximately the same time as valley network activity.

portions, were active slightly later than others (into the Early Hesperian).

To summarize, our results imply that activity in the highlands valleys we measured ended across the highlands by \( \sim 3.5 \) Gyr (in the Hartmann system, see Fig. 4) or \( \sim 3.7 \) Gyr (Neukum system) at the latest. This result is robust in both the ensemble and individual interpretations of our data. Our results are consistent with a global shift in surface conditions at approximately the Noachian/Hesperian boundary (see Figs. 4 and 5). Thus, our observations do not support the interpretation of Craddock and Howard (2002) that there was a “continued erosion and modification in the martian highlands throughout the early history of Mars,” well into the Hesperian and Amazonian, “implying a long-lived episode of valley network formation whose rate diminished through a gradual climate change.”

3.4. Summary: young valley networks

As exemplified by Alba Patera, a few valley systems have been considered on the basis of stratigraphic constraints to be prime candidates for valley network activity in more recent periods of martian history. We have completed buffered crater counts for four such candidate young valley systems: the volcanoes Alba Patera (discussed above), Ceraunius Tholus, and Hecates Tholus (see Gulick and Baker, 1990), and on the rim of Valles Marineris/Echus Chasma (see Mangold et al., 2004). Stratigraphic relationships outlined by these authors for these features suggest that they are unusually young compared to cratered upland valley networks. Our crater counts yield Late Hesperian or Early Amazonian ages for these systems, consistent with the stratigraphic predictions (Table 3, Fig. 4). Again, the fact that these valleys are demonstrably young and separated in time from the cratered upland valley networks is inconsistent with the suggestion of Craddock and Howard (2002) that valley activity in the highlands and on these young surfaces was the same temporal episode of valley network formation, nor that the rate of valley network formation “diminished through a gradual climate change.”

Besides their younger age, these younger valley systems are in specific, isolated locales, and their geomorphology differs in some important respects from cratered uplands valley networks. All four cases of the younger valley systems that we observe also appear to have higher drainage density than typical valley networks in the highlands (Gulick and Baker, 1990). In the case of Ceraunius Tholus and Hecates Tholus, valleys are generally radial from the summit region and have few tributaries downslope, suggesting that the source of water for these valleys may have been concentrated in the summit region. Indeed, we suggest that in the case of Ceraunius Tholus and Hecates Tholus, snowmelt from the near-summit region during active magmatic periods appears to be a plausible mechanism for forming the observed valleys (Gulick et al., 1997; Fassett and Head, 2006; Fassett and Head, 2007b). This mechanism may also explain valley network formation on Alba Pa-
tered, although further analysis of this system is required to explore this possibility.

In summary, although a few valley network systems appear to be unusually young (Figs. 4 and 7), our results suggest that the formation of the highland valley networks, which form the vast majority of the valley networks on the planet, ended at approximately the Noachian/Hesperian boundary. In cases where formation of valley networks occurred in more recent periods, the process was of limited extent, localized to certain regions, and in many cases involved an endogenous component, such as magmatic heating.

4. Discussion and implications

The primary results of our buffered crater counting are that (1) the vast majority of valley networks on Mars, including all the valleys we measured in the heavily-cratered highlands, are ancient (mean age at the Noachian–Hesperian boundary); (2) a few valley-network incised areas are demonstrably younger (Late Hesperian or Early Amazonian); and (3) where younger systems exist, they apparently result from local rather than global processes. Taken together, these results suggest that a widespread change in environmental conditions occurred at approximately the Noachian/Hesperian boundary, causing valley formation to largely cease. This section compares our new results to earlier work and explores the implications for the broader geological history of Mars.

4.1. Crater degradation and the end of highland valley formation

Observations of the fresh crater population of various dissected highlands were completed in two studies by Craddock and Maxwell (1993) and Maxwell and Craddock (1995). Craddock and Maxwell (1993) found that the composite, fresh crater population of the dissected highlands had an $N(5)$ of $197 \pm 4$, at the Noachian–Hesperian boundary (see Tables 1 and 2). This result was confirmed in six regions by Maxwell and Craddock (1995), who found a narrow range of $N(5)$ values between 188 and 251. These imply an Early Hesperian or Late Noachian fresh crater “stabilization” age across the dissected highlands. Our best fit $N(5)$ for the highland valley networks is between 187 (Hartmann best fit) and 215 (Neukum best fit). Thus, there is remarkable consistency between the crater size–frequency distribution of the fresh populations that they measure and the crater population we find in this study. A direct comparison of our results with their “fresh crater” size–frequency data is shown in Fig. 7.

A variety of hypotheses can be put forth to explain this correlation. One hypothesis is that this correlation is a result of causation. In this scenario, favored by Craddock and Maxwell (1993), Maxwell and Craddock (1995), and Craddock et al. (1997), preservation of fresh craters was impossible during the period when valley network formation and fluvial activity occurred on early Mars, due to the effects of precipitation and fluvial erosion. This scenario is consistent with our data, and detailed studies of some large ancient highland craters have demonstrated that they were degraded by fluvial processes resulting in large alluvial fans (e.g., Moore and Howard, 2005). However, it is not entirely clear that fluvial processes were the predominant process of crater degradation in the Noachian. An alternative scenario is that crater degradation was primarily controlled by non-fluvial processes (such as impact degradation; see, e.g., Head, 1975), and that the common decline in crater degradation rates and fluvial activity may not be completely causally related. Further work is needed to constrain crater degradation processes and how these connect to fluvial activity on Early Mars.

4.2. The decline in valley network formation on Mars

Our crater counts suggest that cratered upland valley network activity was confined to a period ending at approximately the Noachian/Hesperian boundary (Figs. 4 and 7). This is consistent with the earlier interpretations and measurements of Pieri (1980a, 1980b), Carr and Clow (1981), and Carr (1995) based on crater counts and stratigraphic observations. Thus, our data lead us to disagree with the notion that fluvial activity on Mars experienced a “slow decline” well into the Hesperian or Amazonian (Craddock and Howard, 2002; Scott et al., 1995; Scott and Dohm, 1992). Valley formation after this time appears to have been an uncommon process resulting from local-to-regional scale geological processes and not a function of global conditions (Fig. 8). Several implications of this steep decline in valley formation at approximately the Noachian/Hesperian boundary are worth considering.

4.2.1. Tharsis

Phillips et al. (2001) showed that highland valley formation appears to post-date the emplacement of the bulk of the Tharsis province, because the Tharsis load was emplaced early enough to help route the long-wavelength direction of valley network flow. In their study, they make the assumption that most valley networks on the planet were emplaced in the Noachian. Thus, our data directly bolster their conclusion that Tharsis was emplaced in the Noachian, since our dates show that cratered upland valley network activity ended by about the Noachian/Hesperian boundary.

4.2.2. Crater lakes

There are many locations where valley networks appear to flow into depressions, usually craters, that are prime candidate sites for lakes on Mars (see, e.g., Irwin et al., 2005a and references therein). It seems likely that the broad decline in valley formation at approximately the end of the Noachian also marks the end of most martian lacustrine activity fed by cratered upland valley networks. Earlier crater counts on the floors of craters suspected of being lakes, however, has led to suggestions that virtually all such lakes were active in the Hesperian and later (Cabrol and Grin, 1999, 2001). The Cabrol and Grin interpretations are inconsistent with our dated decline in valley network activity at the Noachian–Hesperian boundary.

Several possible explanations exist for this discrepancy. One possible cause is technical: the basin floors from which
units appear to have preferentially resurfaced basin and crater floors. A type-example of this phenomenon is Gusev crater, where the young volcanic plains material explored by Mars Exploration Rover Spirit (e.g., Squyres et al., 2004) post-date any lacustrine material associated with Ma’adim Vallis (Greeley et al., 2005).

Thus, the interpretation that many basin and crater plains are substantially younger than the Noachian–Hesperian boundary does not imply that widespread recent crater lake activity has occurred. Although a few examples of younger crater lakes may have formed in association with outflow channels (e.g., Cabrol and Grin, 1999) or with young, isolated fluvial features such as those on Ceraunius Tholus (Fassett and Head, 2007b), it seems unlikely that such lacustrine activity was widespread or in equilibrium with the broader surface environment. Our crater counts indicate that the last, widespread activity in highland valley networks ended near the Noachian–Hesperian boundary, and this makes it highly unlikely that many crater lakes post-date this point, especially if they were sourced by highland valley networks. Where candidate lake basins have floor material with a post-Early Hesperian crater population, a more likely explanation is that the basin floor has been resurfaced by a process unrelated to valley network activity, such as emplacement of Hesperian-aged volcanic plains.

4.2.3. The emplacement of regional volcanic plains

Along with resurfacing the floor of potential lake basins, the widespread emplacement of plains material in the Late Noachian and Early Hesperian has played an important role in post-valley network modification of Noachian highland terrains. A result of this modification is that the present distribution of valley networks on the surface has been altered, as valleys have been buried or embayed by smooth material (e.g., Fig. 1), especially in low-lying portions of cratered upland valley networks. For example, in the 1:15,000,000 scale maps of Scott and Tanaka (1986) and Greeley and Guest (1987), the plateau region of northern Arabia Terra north of dense cratered upland valley networks (Figs. 2 and 4), is largely resurfaced with plains of Late Noachian (Npr, Noachian ridged plains, interpreted to be of volcanic origin) and Early Hesperian age (Hr, Hesperian ridged plains, interpreted to be of volcanic origin). Other potential examples of resurfacing exist in Margaritifer Sinus and western Arabia Terra, where high-standing topography that shows geomorphic signatures of fluvial modification is surrounded by smooth material (e.g., Hynek and Phillips, 2001). Hynek and Phillips (2001) have interpreted these high-standing features as “erosional inliers” that are topographically high remnants of a massively-denuded landscape, with low-lying smooth surroundings eroded to the point of peneplanation. In light of the ubiquity of ridged and smooth plains, however, we favor an alternative view. We interpret these high-standing areas as simply the embayed remnants of dissected terrain, with their low-lying surroundings more extensively resurfaced by volcanic plains material. This emplacement relationship is consistent with other observed relationships between plains units and valley networks throughout the highlands (e.g., Fig. 1; see also, Carr, 1996), since mapped valleys in Margaritifer Sinus

young ages have been derived commonly have relatively small surface areas. In order to obtain reasonable crater statistics, smaller craters than those included in our size–frequency distribution age estimates were used to derive ages. On Mars, crater retention ages derived using small crater sizes usually yield younger ages than ages obtained using large crater sizes, even on the same surface unit. The cause of this discrepancy is the removal of small craters, which are more subject to infilling and/or erosion than their large counterparts (e.g., Hartmann and Neukum, 2001; Hartmann, 2005). The resolution and data quality of the Viking images used in these analyses might also account for fewer small craters and for the youthful basin and crater floor ages derived by Cabrol and Grin (2001).

Alternatively, the young ages of many intra-valley basins and crater floors may indeed be reflective of their surface age. Many of these basins and crater floors have been substantially resurfaced since the Noachian/Hesperian boundary. Ridged and smooth plains units (such as Hesperian ridged plains, Hr) appear to be ubiquitous in the highlands (Fig. 1), and these plains

Fig. 8. At top, a schematic representation of valley network activity over Martian history based on our buffered crater counting results is shown. The majority of highland valley networks were active in the Late Noachian; activity in the highland valley networks we measured ended either at the Noachian/Hesperian boundary or slightly later, by the Early Hesperian. The intensity of valley network activity in the early portions of the Noachian period is not known (arrows and question marks), as our results constrain only when valley formation ended. In younger periods, valley networks formed in certain locations, likely as a result of local processes and conditions. The specific locations of younger valleys we measured are shown. At the bottom, the mineralogical history of Mars derived by Bibring et al. (2006) is presented. There appears to be a slight difference in the interpreted time for when Mars transitioning from being a “phyllolicate-forming” planet and when we date the end of widespread valley network formation (see discussion in text).
and Arabia Terra commonly terminate at the boundary of the smooth material (Hynek and Phillips, 2001). If these smooth plains have simply buried pre-existing dissected terrain, the magnitude of erosion required to explain the observed geomorphology (Hynek and Phillips, 2001) would be greatly reduced.

4.2.4. Evolution in valley network morphology

Harrison and Grimm (2005) have also considered the decline in valley network activity. They argue that during the waning stages of valley network formation on Mars, there was a transition from dense valley networks to sparse networks, a result of a transition from runoff-dominated valley formation to groundwater-dominated formation. The valley networks that we dated include features in each of the morphological classes of Harrison and Grimm (2005). We find no clear correlation, however, between the ages we derive and the two different morphological classes of the valley systems (dense and sparse) defined by Harrison and Grimm (2005).

Other workers have suggested that some of the sparse valley systems (interpreted to be younger and due to sapping by Harrison and Grimm, 2005) can result from processes unrelated to groundwater sapping. For example, an important process for creating sparse valleys on Mars appears to have been basin overflow floods triggered by overtopping of drainage divides (see Irwin and Grant, 2007). Examples of sparse systems listed by Harrison and Grimm (2005) that were clearly affected by this process include Ma’adim Valles, which has a large basin at its head (Irwin et al., 2002), and Scamander Valles, which also has a basin at its headwaters fed by Naktong Valles (Irwin et al., 2005a). Basin overflow floods may also have played a role in establishing the geomorphology of other valleys classified as sparse by Harrison and Grimm (2005), including Huo Hsing Vallis, Licus Vallis, and Mamers Vallis (connected to Scamander). If this is indeed the case, there appear to be only a few clear examples of relatively young, groundwater-dominated valley networks; Nirgal Vallis is perhaps the best example on Mars (Jaumann and Reiss, 2002). Additional analysis is clearly required to define the nature of the terminal stages of cratered upland valley network formation.

4.3. Environmental conditions and implications for valley network formation mechanisms

On the basis of our crater counting results, and related geomorphological and mineralogical studies, inferences can be made about the environmental conditions that prevailed at the time of valley network formation.

4.3.1. Mineralogical data

The widespread presence of surface water suggested by the cratered upland valley networks should have had some influence on the surface weathering environment. Recent mineralogical studies, in particular, the OMEGA instrument, found phyllosilicates on Mars predominantly in Noachian-aged terrains, supporting the idea that the early weathering environment on the planet was dominated by water–mineral interactions (Poulet et al., 2005; Bibring et al., 2006). Bibring et al. (2006) also pointed out that the Noachian weathering environment differed from that of later times, suggesting that a colder and dryer climate had prevailed on Mars since the Noachian. Further analysis by the CRISM instrument (Mustard et al., 2007) substantiates the findings of Bibring et al. (2006) and suggesting that the Noachian crust is highly altered and that more phyllosilicates exist at depth.

Two questions emerge: Is the correlation between valley network formation and Noachian crustal phyllosilicate alteration causal? What is the relationship between the end of the phyllosilicate era and the end of the era of upland valley network formation? In the context of our study, we are particularly interested in the timing derived by the OMEGA team for the transition from phyllosilicate to later weathering environments. Bibring et al. (2006) suggest that this transition took place in the Noachian (Fig. 8), somewhat earlier than the end of widespread upland valley network formation (approximately the Noachian–Hesperian boundary) suggested by our data. There are a several possible reasons for this difference. Widespread valley network activity and phyllosilicate formation may not have ended at the same point in time. For example, the observed upland valley networks might in themselves represent the waning stages of an earlier, much more extensive hydrological cycle, largely responsible for the phyllosilicate alteration. Alternatively, this slight difference between their results and ours may be superficial. For example, it may result from a limited sampling of phyllosilicate environments or stratigraphic exposures, and further observation and analysis may reveal close the gap between the two boundaries. Further work will be necessary to refine the chronological constraints on marker minerals for past weathering environment of Mars, such as phyllosilicates. The new high spatial resolution CRISM data, combined with the context provided by HiRISE imaging data, is beginning to place mineralogical observations in a specific stratigraphic context (e.g., Mustard et al., 2007; Ehlmann et al., 2007). These regional stratigraphic analyses will provide new opportunities to apply crater-counting techniques to the alteration history of the Noachian crust, to address the question of the relationship between valley networks and phyllosilicate formation (e.g., Fassett and Head, 2005; Ehlmann et al., 2007).

4.3.2. Mode and duration of valley network formation

Given that surface conditions apparently differed early in martian history from those in later periods, what do our chronological results have to say about the mode of valley network formation? A widely-held hypothesis is that valley networks formed in an early, terrestrial-like warm and wet climate period (e.g., Craddock and Howard, 2002). In this model rainfall (pluvial activity) was the dominant delivery mechanism of water from the atmosphere to the surface, producing runoff and recharge of subsurface aquifiers. Warm, wet conditions in this scenario are long-lived, as crater degradation throughout the Noachian is interpreted to be due to fluvial erosion linked to pluvial precipitation (Craddock et al., 1997; Craddock and Howard, 2002). Alternatively, a cold early Mars was hypothe-
The timing of valley network formation on Mars

sized by Gaidos and Marion (2003), who attributed valley networks to the transient flow of liquid water at the surface. In their view “formation of copious ground ice in the Noachian and migration of groundwater drove mass wasting and the development of valley networks.” In a variation on the cold early Mars theme, Carr and Head (2003) showed how accumulation of snow in the uplands (nival activity rather than pluvial activity) could cause basal melting and drainage to produce valley networks, particularly in the Noachian when the geothermal heat flux was greater. Thus, two end-member classes of hypotheses exist, one invoking persistent “warm and wet” conditions and one which argues for or “cold and snowy” climate conditions in the Noachian at the time that valley networks formed. Models which are intermediate in terms of climate have also been proposed. Stepinski and Stepinski (2005) examined the maturity of martian drainage basins and, on the basis of their relative immaturity, suggested that the valley network environment was arid, with only periodic or episodic events leading to fluvial activity and erosion.

Another episodic model is that valley networks formed as a result of climate changes triggered by large impacts (e.g., Segura et al., 2002). In these models, large impacts liberate water from some reservoir, leading to precipitation and runoff. The source of water is typically the regolith or upper crust, although certain classes of impactors can also be a significant source of volatiles (Segura et al., 2002; Ong et al., 2007). Initial modeling of the impact-induced climate scenario focused on the aftermath of very large impact events (>500-km diameter crater-forming events) (Segura et al., 2002). More recently, examination of the effects of smaller impact events has begun. This work suggests that such events might be sufficiently energetic to cause significant amounts of precipitation and valley-forming activity (Colaprete et al., 2004). For example, an impact event resulting in a 60-km crater is suggested to be energetic enough to have dramatic regional effects (Colaprete et al., 2004).

For this hypothesis to be consistent with our results, valley formation on the regional-to-global scale has to end at approximately the Noachian–Hesperian boundary. Although the impact cratering rate has decreased substantially since the mid-Hesperian, crater production models predict that there should have been ~200 craters greater than ~60-km in diameter formed on Mars during the latest Hesperian and Amazonian. Indeed, there should even have been a few 60-km diameter craters formed in the last 100 Myr. If craters of this scale commonly triggered intense regional valley activity, as suggested by Colaprete et al. (2004), we might expect widespread valley network activity during post-Noachian geological periods. The lack of young valley networks in the cratered upland terrain, and the very localized nature of valley networks observed elsewhere, suggest that this mechanism is unlikely to the main factor in valley network formation. One possible way of reconciling an impact-induced climate change scenario with our age constraints for the cratered upland valley networks is if the cumulative effect of multiple impacts is important. In this case, if there was a terminal cataclysm or Late Heavy Bombardment on Mars (e.g., Solomon and Head, 2007), it may have delivered water to the surface of Mars and been of sufficient intensity to alter the global climate state and trigger a phase of valley network formation.

Fundamentally, our data place a firm constraint on the cessation of cratered upland valley network activity. Other observations provide information on the intensity and length of valley network formation. One of the strongest such constraints is that some large lakes on Mars were filled, overtopped, and maintained as open systems (e.g., Irwin et al., 2002; Fassett and Head, 2005; Irwin et al., 2005a). The volumes of these lakes are on the scale of terrestrial Lakes Tahoe or Erie (e.g., Fassett and Head, 2005), up to the scale of the Mediterranean Sea (e.g., Irwin et al., 2002). Providing a supply of water sufficient to fill the lakes and trigger outlet discharge requires a minimum of hundreds to thousands of years even with extremely high valley network input flow rates. Climate scenarios in which less intense fluvial activity persisted for a longer period of time would require hundreds of thousands to millions of years to fill and overtop the lakes. These minima are obviously much shorter than the length of the Noachian period, but it remains unclear how long valley network activity lasted. Improved constraints on key climate variables (precipitation rate, evaporation rate) and hydrological parameters (e.g., permeability, infiltration rate) will aid in the future understanding of this problem.

4.3.3. Insight provided by the environments of younger valley networks

Insight into the conundrum of the nature of the Noachian climate may be provided by the environments in which later valley networks form. Our study supports earlier work (e.g., Gulick and Baker, 1990; Mangold et al., 2004) suggesting that a few valley systems are unusually young compared to those in the upland cratered terrain (Figs. 4 and 7). As shown by our sample (Figs. 2 and 4) and previous work (e.g., Brackenridge, 1993; Carr, 1996; Gulick and Baker, 1990; Mangold et al., 2004), these examples (1) are rare in occurrence (compared to the cratered upland valley networks), (2) are widely areally distributed across the planet (in areas not in the cratered uplands), (3) have ages distributed over a very wide range (Figs. 4 and 7), (4) occur in specific geological environments that provide clues to their origin, and (5) are generally considered to have formed in a “cold and dry” environment.

Many of the young valley network examples occur on the flanks of volcanic edifices, extending down the slopes from near the summit. Gulick et al. (1997) called on localized volcano-related geothermal heat to melt permafrost and/or snowpack to form the valleys. Fassett and Head (2006, 2007b), using analogs from the Antarctic Dry Valleys and Iceland snow-capped volcanoes, interpreted the valleys on Hecates Tholus and Ceraunius Tholus to be due to magmatic geothermal heating of summit snowpack, its melting, and flow of meltwater down the flanks of the edifice to cave the valleys. The occurrences of valley networks on the flanks of some, but not all, volcanic edifices was attributed to the necessity of having climatic periods of summit snow and ice accumulation coincide with periods of magmatic activity in the volcano. In the case of Ceraunius Tholus, Fassett and Head (2007b) showed that the largest val-
ley exited from the summit depression and extended down to the base of the volcano, where it cut into an elongated impact crater, forming a delta-shaped structure on the edge of the crater floor. They interpreted these observations to represent glacial meltwater draining from a summit lake, flowing down the side of the edifice and filling the impact crater, and forming a depositional fan at the entrance to the lake. Periodic sources of water to provide the summit snowpack during a generally cold and dry climate era could come from mobilization and transport of polar ice during periods of higher obliquity (e.g., Forget et al., 2006) or from episodic input of water into the atmosphere from catastrophic flooding events, such as the formation of outflow channels (e.g., Baker et al., 1991; Baker, 2001). In summary, valley formation in these locales (as well as crater flooding and fan emplacement) apparently took place under conditions similar to the cold and dry climate of the present day, which differs greatly from the “warm, wet” scenario hypothesized by Craddock and Howard (2002) for the Noachian. As noted by Gulick and Baker (1989), because these young valleys systems formed in conditions similar to those of today, the hypothesis that highland valley networks may have formed under “cold, dry” conditions should continue to be considered possible.

A second type of location in which young valley networks formed is on the rim and floor of Valles Marineris (e.g., Mangold et al., 2004), where dendritic valleys with a high degree of branching occur. Formed in the Early Amazonian (Fig. 8), these features are interpreted by Mangold et al. (2004) to represent fluvial activity during an era when Mars is otherwise thought to have been cold. They interpret the valley networks to be the result of an anomalous period of warm climate, permitting precipitation and stability of water on the surface and its flow to produce valley networks. However, in order to explain the very limited global distribution of the features (only at Melas and Echus) by this atmospheric mechanism, they require subsequent mantling processes to cover up other examples. An alternate explanation could be that the location of these features is related to the formation of outflow channels (the source regions are predominantly in this area) and the adjacent plateaus could be localized environments of condensation and runoff, thus not requiring a sustained period of “warm, wet” conditions.

A third type of young valley network location is found locally in association with young impact large craters, such as Cerulli (e.g., Brackenridge, 1993). These networks are relatively small and are localized to the crater interiors (e.g., the walls of Cerulli), rims, and ejecta deposits (e.g., Sinton Crater; Morgan and Head, 2007). Occurrence in association with impact craters is easily understood in terms of the direct heating associated with impact events and the local melting of permafrost or ground ice and snow deposits (Rathbun and Squyres, 2002) to produce valley networks. These types of occurrences are thus consistent with localized formation in the cold, dry, post-Noachian climate.

In summary, the geological environments in which the younger, post-Noachian valley networks occur suggest that they are formed by: (1) sources of water localized in space and time (e.g., climate change, outflow channel formation), and (2) specific localized heat sources (related to magmatic intrusion or impact events). All of these geological settings can occur in a cold and dry climatic environment, similar to that of today. Thus, hypotheses for the formation of Noachian valley networks that involve cold and dry climatic conditions, rather than warm and wet conditions, should continue to be considered possible. The valley networks in the cratered highlands, which we demonstrate generally ceased forming at approximately the Noachian/Hesperian boundary, are different in some important respects from these younger examples, as they are globally distributed (see, e.g., Fig. 2), required recharge and a substantial volume of water to form (Carr, 1983, 1996; Goldspiel and Squyres, 1991; Gulick, 2001), and formed large lakes on the surface (Irwin et al., 2005a and references therein). However, it remains unclear that a continuous warm, wet climate with a long-lived period of pluvial activity is a requirement for formation of the Noachian valley networks.

5. Conclusions

Buffered crater counting provides a new way of constraining when valley networks were active on Mars. Applying this technique to thirty valley network-incised regions, we find that the ‘classic’ cratered upland valley networks were active only during the earliest portion of martian history. Individual best-fit ages that we derive for the highland valleys mostly date to the Late Noachian, though in a few cases they extend into the Early Hesperian (Table 3, Fig. 4). Aggregation of all the counts derived for cratered upland valley network-incised terrain, to improve our counting statistics, yields ages of 3.53 Gyr (Hartmann system) or 3.75 Gyr (Neukum system), at the Noachian–Hesperian boundary (Tables 1 and 2; Figs. 5 and 7). Based on this aggregated data, the Noachian–Hesperian boundary is a good marker of the time that valley network activity essentially ended across the martian highlands. Given the widespread distribution of valley features, the termination of highland valley network formation at this point is likely a result of a fundamental shift in the environmental conditions of the martian surface.

In a few locations on Mars, primarily in volcanic environments outside the heavily-cratered highlands, our crater counts of valleys on Alba Patera, Ceranuus Tholus, Hecates Tholus, and the rim of Valles Marineris support the idea that limited valley network activity occurred in more recent times (Late Hesperian or Amazonian) (Fig. 8). This conclusion is statistically robust, and these younger systems have superposed crater populations that are a factor of 2–3× less dense than for valleys in the cratere uplands. These young valley systems are of more limited extent than counterparts in the cratered highlands, are localized to certain regions and likely resulted from local processes or conditions (such as magmatic heating) rather than global environmental conditions.

A few implications of the timing of this decline in valley network activity are worth considering. First, a strong correlation exists between the timing of the end of widespread valley network activity and measurements that suggest a decline in the modification or degradation of craters in the Late Noachian.
or Early Hesperian (Craddock and Maxwell, 1993; Maxwell and Craddock, 1995). Second, previous studies that have suggested young (Hesperian or Amazonian) ages for potentially flooded basins or lakes on Mars, fed by highland valley networks, should be reconsidered. The young age on some basin floors may be due to widespread resurfacing of low-lying areas by smooth volcanic plains.

In summary, most valley network formation on Mars ended at approximately the Noachian/Hesperian boundary (see Fig. 8). Our results are consistent with a Noachian environment where surface conditions at least occasionally allowed fluvial erosion across the cratered uplands, enhanced crater degradation, and a weathering environment favoring the formation of phyllosilicates. The Hesperian–Amazonian environment was more similar to the hyperarid cold desert of today, without widespread valley network formation; moreover, when valleys formed, it was a result local, rather than global, environmental conditions.

Acknowledgments

We thank Misha Kreslavsky for helpful discussions in the preparatory phase of this project, and Daniel Berman and Stephanie Werner for helpful reviews that improved the quality of our manuscript. We gratefully acknowledge financial support from the NASA Mars Data Analysis Program (NN04GI99G), the NASA Mars Express Participating Scientist Program (JPL1237163), and the NASA AISR program (NNGO5GA61G) (to J.W.H.), as well as the NASA Graduate Student Research Program (to C.I.F.). We acknowledge the science and engineering teams of all the instruments and missions from which data were incorporated into this study; in particular, we are especially grateful to the HRSC Experiment Teams at DLR Berlin and Freie Universitaet Berlin, as well as the Mars Express Project Teams at ESTEC and ESOC, for their successful planning and acquisition of the HRSC data and for making processed data available to the HRSC team. We acknowledge the efforts of the HRSC Co-Investigator team who have contributed to this investigation in the mission preparatory phase and via helpful scientific discussions.

Appendix A. Production function and period boundaries

The period boundaries for Mars were defined by Tanaka (1986) using a power law with a power law slope of −2. Both the Hartmann and Neukum Production functions we utilize have a different power law slope across the range of crater diameters we utilize (see discussion in Hartmann and Neukum, 2001, pp. 186–190). This means that even if we assume that the production function being used is correct, a single observed crater size–frequency distribution which falls near a period boundary may have a different period assignments in different diameter ranges because of the “intrinsic fuzziness” (Hartmann and Neukum, 2001) of using these power law slope −2 boundaries with isochrons of different shapes. This effect can cause some uncertainty in the period assignment for crater populations measured on Mars.

Workers have attempted to avoid this issue in a variety ways. The solution utilized in Hartmann and Neukum (2001) was to rely upon the $N(1)$ values proposed by Tanaka (1986) as the fixed period boundaries and extend these to other portions of the crater-size frequency definition using the shape of their production functions. This solution is reasonable, but because of the differing shapes of the Hartmann and Neukum system it would imply (1) a comparatively young Noachian/Hesperian (N/H) boundary in the Neukum system, with $N(5)$ of only 148 for the boundary, significantly less than the $N(5) = 200$ (in the Tanaka definition), and (2) a comparatively old N/H boundary in the Hartmann system, with $N(5)$ of 240. This large difference is problematic, especially when a worker is faced with the practical task of deciding whether a given crater count is Noachian or Hesperian.

An alternative possibility presented by Hartmann (2005) is to simply present the period boundaries as an age range, but we believe this is also an undesirable solution, because it allows units with the same best-fit Hartmann age to be assigned to different periods by different workers, or even by the same worker in different papers.

Thus, we have taken a different approach, and recalculated the fixed period boundaries in both the Neukum and Hartmann system using the Tanaka definitions that are in the size ranges typically most relevant to a unit of a given age. For this approach, the Late-to-Mid Amazonian, the Mid-to-Early Amazonian and the Late Hesperian to Early Amazonian boundaries are defined using the Tanaka (1986) $N(2)$ boundary; the Early-to-Late Hesperian and Late Noachian–Early Hesperian boundary are defined using $N(5)$; and the Mid-to-Late Noachian and Early-to-Mid Noachian boundaries are defined with $N(16)$. Results of this calculation are shown in Tables 1 and 2.

If future refinements of the period boundaries for Mars occur, significant work needs to go into making the definitions consistent and reconcilable with the actual size–frequency distribution shape of the production function for Mars. When this occurs, our counts can be compared with these new isochrons easily and our period assignments can be updated.

Appendix B. Age determination and fitting to isochrons

The method used to calculate best-fit ages and errors for both Hartmann and Neukum isochrons is a weighted least-squares approach. We apply this as follows: we first count craters and derive the appropriate count area using our buffering approach. From these data, we derive the observed size–frequency distribution. Then, we use weighted least squares to minimize the misfit of the observed distribution to the production function being considered, with the weight value for each data point coming from counting statistics. This best-fit isochron gives an age in the Hartmann or Neukum system, and allows us to quantify the quality of the fit of the data to the production function. We combine this with uncertainties derived from counting statistics alone to derive the range of uncertainty in age.

The different assumptions that underlie the Hartmann and Neukum production functions lead to differences in how we apply the least-squares fitting to each approach. The most im-
Fig. 9. Mapped valley networks and craters (left), cumulative crater-size frequency distribution (center), and incremental size–frequency distribution for the 30 valley network counts. For each point on the crater-size frequency diagram, the 90%-confidence interval is calculated using the inverse gamma function. Use of this confidence interval instead of the typically utilized root-$N$ better represents the age estimate implied by a small numbers of craters. 90%-confidence upper limits (triangles) also are given in the incremental plot for bins where no craters are observed.
The timing of valley network formation on Mars

Fig. 9. (continued)
Fig. 9. (continued)
Fig. 9. (continued)
Fig. 9. (continued)
Fig. 9. (continued)
Fig. 9. (continued)
important difference is that for the cumulative analysis, we choose to truncate the crater-size frequency data at 20 km and utilize data only smaller than this size. To implement this truncation, the $N(20)$ value was established for each cumulative size–frequency distribution by iteratively assigning it the value for the best-fit Neukum isochron to the observed size–frequency data in the 2 to 20 km diameter range.

The decision to truncate the cumulative size–frequency distribution addresses the fact that the cumulative distribution can be significantly affected by the presence or absence of rare, large craters, because measurements at large crater sizes propagate to smaller sizes as well. Truncating the cumulative size–frequency distribution also helps to avoid the potential effect of count incompleteness that may arise at large sizes. At some size, craters become of such great extent that they are effective at erasing valleys over an entire area. This can cause any pre-impact valley network to be unmappable, and also render the crater uncountable, because the crater may not be clearly superposed on a mappable valley system.

For these reasons, we believe that utilizing this truncation is preferred. However, to verify that this truncation does not affect our broad results, we have compared the effects of this truncation with untruncated data. Truncating the cumulative size–frequency distribution increases the derived $N(5)$ for our valley network counts by $\sim 10\%$. Not truncating the cumulative size–frequency distribution has only minor effects on our period assignments; it would change the “Neukum period” of three highland valleys from the Late Noachian to Early Hesperian (valley networks 3, 6, and 25) and one highland valley network from the Middle Noachian to the Late Noachian (valley network 5). It would also change our assignment of the valleys on the volcano Ceraunus Tholus (valley network 28) from the Late Hesperian to the Early Amazonian. None of these changes would affect the broad conclusions of this study.

References


The timing of valley network formation on Mars


