CRATERING CHRONOLOGY AND THE EVOLUTION OF MARS

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Abstract. Results by Neukum *et al.* (2001) and Ivanov (2001) are combined with crater counts to estimate ages of Martian surfaces. These results are combined with studies of Martian meteorites (Nyquist *et al.*, 2001) to establish a rough chronology of Martian history. High crater densities in some areas, together with the existence of a 4.5 Gyr rock from Mars (ALH84001), which was weathered at about 4.0 Gyr, affirm that some of the oldest surfaces involve primordial crustal materials, degraded by various processes including megaregolith formation and cementing of debris. Small craters have been lost by these processes, as shown by comparison with Phobos and with the production function, and by crater morphology distributions. Crater loss rates and survival lifetimes are estimated as a measure of average depositional/erosional rate of activity.

We use our results to date the Martian epochs defined by Tanaka (1986). The high crater densities of the Noachian confine the entire Noachian Period to before about 3.5 Gyr. The Hesperian/Amazonian boundary is estimated to be about 2.9 to 3.3 Gyr ago, but with less probability could range from 2.0 to 3.4 Gyr. Mid-age dates are less well constrained due to uncertainties in the Martian cratering rate. Comparison of our ages with resurfacing data of Tanaka *et al.* (1987) gives a strong indication that volcanic, fluvial, and periglacial resurfacing rates were all much higher in approximately the first third of Martian history. We estimate that the Late Amazonian Epoch began a few hundred Myr ago (formal solutions 300 to 600 Myr ago). Our work supports Mariner 9 era suggestions of very young lavas on Mars, and is consistent with meteorite evidence for Martian igneous rocks 1.3 and $0.2 - 0.3$ Gyr old. The youngest detected Martian lava flows give formal crater retention ages of the order 10 Myr or less. We note also that certain Martian meteorites indicate fluvial activity younger than the rocks themselves, 700 Myr in one case, and this is supported by evidence of youthful water seeps. The evidence of youthful volcanic and aqueous activity, from both crater-count and meteorite evidence, places important constraints on Martian geological evolution and suggests a more active, complex Mars than has been visualized by some researchers.

1. Background: Cratering Studies and the Relation to Martian Rocks

Through the process of impact cratering, Nature randomly stamps circular bowls of known shape on planetary surfaces. This fact offers us a tool for interpreting planetary surfaces. Though the accumulated numbers of impact craters, we can assess ages. Through the modification of the crater shapes by erosion, dust deposition, lava flow coverage, etc., we can assess geological processes of the planet.

In this volume Stöffler and Ryder (2001) summarized the basic radiometric dating that dates lunar surfaces, and correlates with impact crater density. Neukum *et al.* (2001) laid out evidence that the shape of the crater size distribution and

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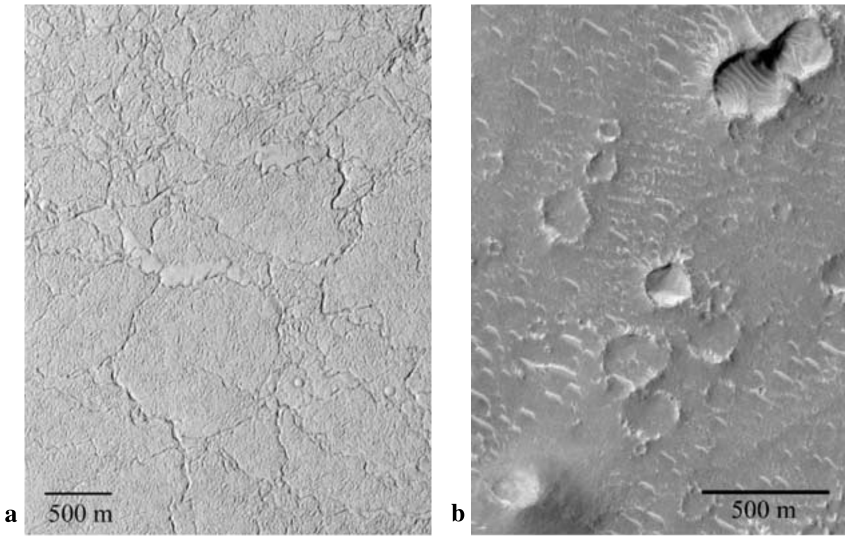

Figure 1. Comparison of young and old Martian surfaces. a) On a relatively fresh lava flow, such as this example in Amazonis Planitia at latitude 25.4 N, longitude 166.5 W, the lack of accumulated impact craters directly reflects the young age. b) On the older highland surface in Isidis Planitia, shown here, crater density is higher, and dust drifts cover small craters at latitude 8.4 N, longitude 276.5. The net effect of such dust drifts is to obliterate small craters preferentially, relative to larger craters in older areas. MGS images M00-00536 (a) and FHA-00521 (b). All MGS images in this chapter are courtesy Malin Space Science Systems and JPL Mars Global Surveyor Project.

time dependence of cratering is known in the inner solar system. They show that a relatively uniform shape of size distribution is observed on relatively undisturbed surfaces, such as lunar maria, lunar ejecta blankets, and some asteroids. This shape – more specifically the number of craters/km^2 produced on a surface in a given time as a function of diameter D – is called the “production function” for impact craters. Ivanov (2001) derives the cratering rate of Mars relative to the moon. Combining the results of those chapters, we know the rate of production of craters on Mars of any given size, and hence the absolute crater retention age of different stratigraphic units on Mars within an uncertainty factor of about two or three.

For a surface undisturbed by non-impact processes, e.g. a deep lava flow covering a large area, the analysis of accumulated craters to determine an age is conceptually straightforward (Figure 1). This situation is approached in the lunar maria, which formed mostly between about 2.9 and 3.9 Gyr ago – a factor of only 1.3 in age. However, the relatively active geology of Mars produces a more complex case than the moon. Younger lava flows may interfinger with older background surfaces with higher crater density. Martian rocks as well as crater counts show that Martian lava flows cover a much larger range of age, a factor of 100 or more.

“Crater retention age” (CRA) was defined by Hartmann (1966a) as the average time interval during which craters of diameter D are preserved on a given surface. For a young lava flow, where no craters have been lost, it should be the age of the flow itself. For older surfaces, it is D-dependent and refers to the preservation time of the craters. For example, on an idealized surface, with constant net accumulation of dust on crater floors, small craters would be obliterated faster, and the CRA would be small for small craters, and larger for larger craters. For the largest craters the CRA may indeed be the age of the formation of the surface.

Various stratigraphic units have been mapped on Mars and their relative ages have been determined by a combination of superposition relations and crater densities (Tanaka, 1986; Scott *et al.*, 1987). In principle, absolute ages can be estimated through impact crater densities. However, the absolute chronology and absolute ages of different Martian stratigraphic units have been known only crudely due to uncertainties, primarily in the Martian impact flux and methodologies used to scale the lunar cratering to Mars. Viking and Mariner 9 analysis produced a wide range of chronologic systems, with no clear consensus on absolute ages (Hartmann, 1973; Soderblom *et al.*, 1974; Neukum and Wise, 1976; Hartmann *et al.*, 1981; Neukum and Hiller, 1981; Strom *et al.*, 1992).

In recent years, as developed in detail throughout this book, the absolute Martian chronology has been loosely constrained by two complementary data sets.

First, as discussed by Nyquist *et al.* (2001), Martian meteorites give precise radiometric crystallization ages for rocks from a small number ($4 - 8$) of impact sites on Mars. The nakhlites and Chassigny appear to represent a mafic igneous intrusion 1.3 Gyr ago, and the basaltic shergottites appear to represent surface flows somewhere on Mars about $165 - 475$ Myr ago. In addition, one Martian meteorite, ALH84001, gives a crystallization age of 4.5 Gyr and with subsequent carbonate formation at about $3.9 - 4.0$ Gyr ago, and little subsequent. This sample suggests that in at least some regions, primordial crust is not only preserved but also exposed, relatively near the surface. Cratering studies (Melosh, 1989) indicate that the ejected rocks are likely to come from near surface layers, no more than a few hundred meters down, although this is not regarded as proven, because the impact models to not appear to have reached a state of sophisticated maturity.

The Martian impact sites not only reveal recent igneous activity, but also show evidence of liquid water-based activity after the rocks formed. Shih *et al.* (1998) and Swindle *et al.* (2000) dated weathered minerals in the 1.3 Gyr-old nakhlite, Lafayette, concluding that it had been exposed to liquid water around 670 Myr ago. In a similar vein, Sawyer *et al.* (2000) and Bridges and Grady (2000) find that the nakhlites Lafayette, Nakhla, and Governador Valadares all contain evaporite minerals, such as gypsum, anhydrite, and clays, caused by exposure to evaporating, seawater-like brines more recently than 1.3 Gyr ago. In addition, Malin and Edgett (2000a) identified water seeps and resultant gullies on crater-free hillsides that are relatively free of dust accumulation; these have unknown ages, but appear to have less dust cover than some of the young lavas (Hartmann, 2001).

In summary, the available Martian rocks establish a Martian chronology of igneous activity and water based weathering that stretches from the beginning of Martian history to the last few percent of Martian time.

The second constraint on Martian absolute chronology is the impact record, and it appears consistent with the rock data. Crater counts on different units, especially since Mars Global Surveyor (MGS) imagery was available, show a wide range of ages, including geologically young activity. The earliest Mariner data, from 1965 to 1971, revealed heavily cratered areas where the largest craters, $D > 64$ km, had crater densities similar to those in the lunar highlands, with inferred ages of the order $3.8 - 4.5$ Gyr (Leighton *et al.*, 1965). In these same regions, smaller craters ($250 \text{ m} < D < 16 \text{ km}$) have lower numbers than in the lunar highlands and a wide range of degradation states, suggesting losses of smaller craters by erosion and deposition, as first suggested by Öpik (1965, 1966). Similar losses of small craters occur on Earth. The numbers and losses of craters of various smaller diameters and depths offer a way to characterize “crater retention ages” and the rate of geologic activity in terms of the time scale needed to fill or obliterate the craters, as discussed by Hartmann (1966a). Much of the early, Mariner-era work was devoted to deciphering the history of obliteration processes, and generally suggested that the craters revealed strong obliteration, with a higher rate in early Martian history (Öpik, 1965, 1966; Hartmann, 1966a, Hartmann, 1971; Chapman *et al.*, 1969; Jones, 1974; Soderblom *et al.*, 1974). From Mariner 9 images, Hartmann (1973) derived $3 - 4$ Gyr ages in the uplands, along with enhanced erosion/deposition in early Martian time, but also proposed volcanic activity about 300 Myr ago in Tharsis, and this was supported this with later analysis of the impact rates and (Hartmann, 1978; Hartmann *et al.*, 1981). Several other early chronological studies of the 1970s (Soderblom *et al.*, 1974; Neukum and Wise, 1976) derived somewhat older ages for the upper Amazonian volcanic features, emphasizing that most Martian geologic activity was concentrated in an early period. Later efforts, such as Neukum and Hiller (1981), Hartmann (1998), and the Martian rock data (Nyquist *et al.*, 2001) allowed for of a tail of igneous and other activity extending into the present. MGS confirmed massive layering and mobility of dust and fine material on Mars (Malin *et al.*, 1998), which supports the idea that small craters are removed by erosional/depositional effects, as on Earth, and this must be taken into account when interpreting crater retention ages (see also Greeley *et al.*, 2001). One way of expressing the modern issue is to ask about the frequency distribution of igneous, erosional, and depositional activity as a function of time.

The crater-dating results and the Mars meteorite results are independent, and their present agreement gives some confidence that the two methods give accurate ages. The early suggestions of young igneous units on Mars in 1973 came before any meteoritic suggestion of young igneous activity. Papanastassiou and Wasserburg (1974) noted that Nakhla’s properties implied late formation on a body that might be bigger than most asteroids, but that body was still unknown. Just before the wide recognition of young Mars meteorites, NASA convened a “Basaltic Volcanism Study Project,” within which a consortium including Strom, Shoemaker, Weidenschilling, Chapman, Dence, Grieve, Hartmann and others used asteroid/comet data to estimate relative Mars/moon cratering rates, and then used crater counts by various researchers to infer Mars ages – an antecedent of the method used here. The consortium concluded that the Martian uplands are very old, but that some of the younger plains of Mars, such as the Tharsis volcanism, had ages in the range of a few hundred Myr to around 2.0 Gyr (Hartmann *et al.*, 1981). The recognition of similar Mars meteorite ages culminated a year or two after that work was done. Suggestions began to be floated as early as 1979-81 that Mars might be a source for such objects (Nyquist *et al.*, 1979; Wood and Ashwal, 1981) but acceptance of this idea came a few years later when Martian atmospheric gases were found in them (Bogard and Johnson, 1983).

Mars Global Surveyor, orbiting Mars since 1997, added a new twist to the understanding of the youngest volcanic units, by means of much higher resolution images (1.5 m/pixel). In certain restricted areas, such as Elysium Planitia, these revealed lava flows with fresh surface textures and very sparse numbers of well-preserved impact craters (Keszthelyi *et al.*, 2000). For some flows, initial counts suggested densities of small craters of the order of one percent those of the lunar maria, implying ages of <100 Myr, possibly <10 Myr (Hartmann and Berman, 2000). This work affirmed a conclusion by Plescia (1990) that Elysium Planitia has very young lavas. In addition, other early MGS analyses pointed to other broad areas of lava flows, such as the Tharsis volcanoes and Amazonis Planitia, where ages of at least some flows appeared to be <100 Myr. Thus, the cratering data independently support the conclusion from the Mars meteorites that igneous geologic activity on Mars has persisted from early times down to the present geologic era, though the rate may have decreased, since the youngest flows are rare.

The meteorite data and the cratering data are complementary in another way. Meteorites give good ages but poor statistical sampling of Mars; craters give poorly constrained ages but good statistical sampling of known units. These units may not be studied by sample return or in situ studies for decades to come. A major goal of this chapter and earlier chapters is to refine the methodology and tie these two complementary systems together, so that crater densities can give reasonably accurate absolute ages (potentially within 20%) for all stratigraphic units, and can be tested for consistency with the known Martian rock samples.

2. Issues with Regard to Crater Count Chronologies on Mars

The crater count methodology has several fundamental limitations. First, the total crater density is measured by statistically fitting the crater count data (size distribution) to the known production function over a wide range of D. The fit, by least squares techniques, is limited to about 10% accuracy, and curves fit to data from different workers on the same images have about the same level of repeatability (Hartmann *et al.*, 1981). Neukum and co-workers achieved a higher degree of accuracy and repeatability by using stereo coverage of many units, such as in their lunar work (Neukum, 1983; Neukum *et al.*, 1975).

A second limitation is that several slightly different definitions for the boundaries of a given stratigraphic unit, such as a particular set of lava flows or a putative paleolake deposit, may exist. Thirdly, the crater retention age for a given unit, such as a sequence of lava flow, represents only a new age, biased towards the younger surface subunits. Fourth, in order to extend the crater counts to larger diameters, it is necessary to cover larger areas in order to achieve good statistics, and this may be in conflict with the need to define a specific small geologic unit.

Hartmann *et al.* (1981) and Lissauer *et al.* (1988) reviewed these problems and concluded that crater counts generally give repeatable characterization of overall crater density and relative ages of various units to an uncertainty factor of about 1.2 to 1.3. These issues suggest an ultimate limit of perhaps 5% to 20% uncertainty in ages simply due to the process of defining a homogeneous geologic unit, and gathering good cratering statistics, not counting the (presently larger) uncertainties in crater production rate R_{crater} on Mars relative to the moon.

These issues are exacerbated by a peculiar circumstance of Martian spacecraft exploration to date. Mariner 9 and the two Viking orbiters carried low resolution cameras and MGS carried a high resolution camera. With the exception of a small number of late Viking and early MGS images, there is a “hole” between the two data sets, such that it is difficult to get good mid-size crater statistics at $D \sim 250$ to 500 m. Also, MGS does not give 100% areal coverage, so that the small crater populations in broad units must be characterized by “postage-stamp” samples. This leads to problems of characterizing the small crater populations of broad units.

3. The Importance of the R_{bolide} Value

Hartmann (1977) and Hartmann *et al.* (1981) stressed that the modern-day ratio of Mars/moon cratering (expressed in terms of bolides/km^2-yr, which is convertible to craters/km^2-yr at a fixed crater diameter, as shown by Ivanov, 2001) is a critical, measurable parameter for determining Martian surface ages, and hence the overall chronology of Mars. Any estimate of the Martian absolute chronology involves, implicitly or explicitly, an estimate of the Mars/moon cratering rate ratio, R. Hartmann (1977, 1999) adopted this approach and defined the ratio R, which is developed by Ivanov (2001), in terms of

$$R_{\text{bolide}} = [\text{bolides}/\text{km}^2-\text{yr on Mars}]/[\text{bolides}/\text{km}^2-\text{yr on the moon}] \qquad (1)$$

at a fixed bolide diameter. This can be derived from direct observations, as discussed in more detail by Ivanov (2001), and also from dynamical considerations involving asteroid and comet populations, as treated by Bottke (in preparation). This leads in turn to the definition of

$$R_{\text{crater}} = [\text{craters}/\text{km}^2-\text{yr on Mars}]/[\text{craters}/\text{km}^2-\text{yr on the moon}]. \qquad (2)$$

Neukum and Ivanov (1994) and, more explicitly, Ivanov (2001) show that R_{crater} is a function of crater diameter, because of factors involving the slope of the size distribution and also the transition from simple to complex craters.

The largest current uncertainty is in R_{bolide}. A review of recent estimates suggests that the uncertainty is as much as a factor 2 in either direction, caused partly by an uncertainty in the contribution of cratering by comets. As reviewed by Ivanov, our estimate of R_{bolide} is primarily based on asteroids. From tabulations of known Mars- and Earth-crossing asteroids, Ivanov (2001) derived $R_{\text{bolide}} = 2.0$, and Bottke (personal communication, 1999) also derives $R_{\text{bolide}} = 2.0$ from dynamical studies of asteroid feeding mechanism.

The treatment by Ivanov (2001) is currently the best available summary of R_{crater} and its application to Mars chronology. Figure 2 introduces the resulting crater count diagram, and plots the isochrons derived by Ivanov from the Neukum data and from the Hartmann data, along with the isochrons derived below for other ages. "Isochron" is defined as the number of craters that would be produced on a single surface of specified age, and would be still visible today in the absence of any obliterative effects. As seen in Figure 2, the Neukum and Hartmann isochron systems, each with its own independent history stretching over more than 20 years, lie within a few percent of each other 125 m $< D <$ 1 km and at 22 km $< D <$ 45 km, but differ by as much as a factor 2 to 3 at diameters around 2 to 11 km.

The difference at 2 to 11 km apparently stems from differences in our original data bases of post-mare impact craters. We independently averaged over different lunar mare units to characterize the mare crater density. We are still investigating this difference; it illustrates the danger of basing age determinations on too narrow a range of D. However, we are gratified at the close agreement over most of the D range, which shows that a good fit of crater data to isochrons should be possible if crater counts are used over a sufficiently wide range of D. Based on our entire discussion, we believe we can use crater count data to fit isochrons with an effective 1-sigma uncertainty of about a factor 2 in the age determination.

Figure 2 shows the isochrons in a format developed by Hartmann and co-workers for MGS data, but the remaining plots of data in this paper several different formats. The first two formats are "standard formats" recommended by a cratering consortium (Crater Analysis Techniques Working Group "CATWG," 1979). These formats have both advantages and disadvantages. The first is cumulative, which has an advantage of smoothing the data, but the disadvantage of suppressing any turndown in crater population toward smaller diameters. For example, in an incremental plot, removal of craters smaller than D due to flooding of an area by a lava flow would produce an dramatic turndown in an incremental curve, while the cumulative plot merely levels off. Also, the CATWG group recommended using equal scales for the ordinate and abscissa, but this makes the curve is graphically so steep that it is hard to see structure in the curves or differences between them. The second plot, known as the R-plot, plots the data in increments of log D relative to an arbitrary -2 power law, which approximates the size distribution of larger

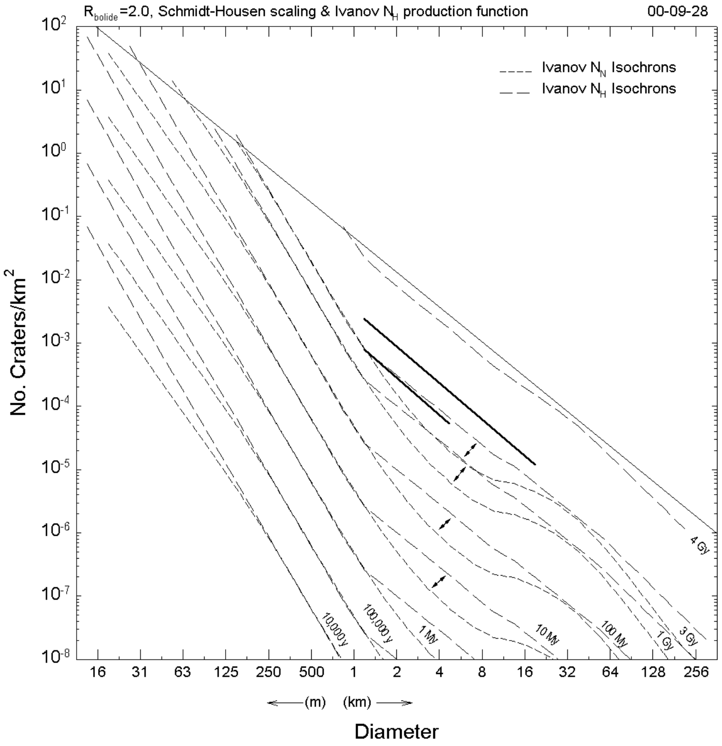

Figure 2. Comparison of isochrons derived by Ivanov (2001) from lunar crater count data by Neukum (it upper curve of each pair) and independent lunar crater count data by Hartmann (*lower curve*). The isochrons from the two independent sources mostly average within 30% of each other, but in the few-kilometer diameter range have discrepancies of a factor 2 to 3. The agreement, combined by the uncertainty in R_{crater} (see Ivanov, 2001) gives a measure of the uncertainty of derived ages. We estimate this uncertainty at a factor about 2. Top solid line shows saturation equilibrium level (see Figure 3). Short solid lines show definitions by Tanaka (1986) of boundaries between Amazonian (*bottom*), Hesperian (*middle*), and Noachian (*top*) Periods. See text for derivation of isochron positions. Figure a) shows standard cumulative format and b) shows the "*R*"-plot, both as defined by Crater Analysis Techniques Working Group (1979). Figure c) shows the log differential plot, as developed for Mars Global Surveyor (*see text*).

craters. The *R*-plot magnifies structure in the curves and discrepancies between various curves, which has both advantages and disadvantages. The concept is less obvious for readers not involved in the cratering field. It can lead to discussion of "structure" that may be noise, and the reference line of −2 slope is not especially significant, since it is not directly observed in any population. For these reasons, the third format, mentioned by CATWG (Appendix I), was chosen and developed by Hartmann and colleagues for the MGS data sets. This is designed to follow the design principle that a graph is easiest to read if the average apparent slope is near 45°. It plots numbers of craters in logarithmic increments in D, giving sensitivity to turndown, and it also gives numerically the same slope as the cumulative plot.

In addition to Ivanov's basic 3.4-Gyr isochron, Figure 2 shows isochrons for other surface ages on Mars. We will now derive those isochrons. The time behavior of the cratering rate, as measured in the Earth-moon system, is fairly well known (Stöffler and Ryder, 2001; Neukum *et al.*, 2001; Ivanov, 2001). Neukum (1983) gave a numerical solution for this time dependence, quoted by Neukum *et al.* (2001, Equation 5). The Neukum time dependence indicates that the isochron for 4.0 Gyr age should be about 16 times higher than that for 3.4 Gyr.

An upper limit exists near this point. Hartmann (1966b) showed empirically that the lunar upland crater density at $D > 2$ km is a factor of 32 higher than that for average mare. Hartmann (1984), Neukum and Ivanov (1994), and Hartmann and Gaskell (1997) have shown that craters reach a saturation equilibrium curve at this level, corresponding to ages greater than $\sim$4 Gyr. This result on saturation is also confirmed by Phobos (Figure 3a), which, orbiting above the Mars atmosphere, has no losses due to the Martian surface erosion regime, and displays cratering that accurately fits the saturation equilibrium curve defined by Hartmann (1984; Figure 3b). This saturation equilibrium curve is thus viewed as the empirical upper limit for crater density, and is shown by the heavy solid curve that bounds the top of Figure 2. Neukum and Ivanov (1994) noted that the shape of the saturation equilibrium curve depends in principle upon the input production function size distribution, although the general level, for the known size distributions, is expected from numerical simulations to lie at the level of the curve shown here (Hartmann and Gaskell, 1997). We believe that the saturation curve is not a precise fixed limit, but fluctuates around the curve shown here, as time goes on, depending on factors such as the age and location of the last largest impact basin (which can spread ejecta, obliterate craters, and reset the surface age at sites near the basin).

Precise isochrons between 4.0 and 3.4 Gyr are hard to map because the cratering rate declined rapidly during this period. On the positive side, any counts falling above the 3.4 Gyr isochrons are restricted to a very early era of Martian history and thus have value in constraining geophysical evolution. Isochrons for ages younger than 4 Gyr have the shape of the production function, except that they truncate where they hit the saturation level, because crater densities can't easily rise above this level. We adopt the argument by Neukum *et al.* (2001) that the shape of the isochrons, i.e. the production function, has been constant through time, though Strom *et al.* (1992) have suggested that it was different in the earliest history of Mars. Counter arguments are given elsewhere (Hartmann, 1984, 1999).

Starting with Ivanov's isochron for a 3.4 Gyr surface on Mars, we now derive isochrons for younger ages. We use the Neukum (1983) time dependence, which shows the cratering rate declining somewhat after 3.4 Gyr ago and leveling out by 3 Gyr ago. As reviewed by Stöffler and Ryder (2001), Neukum *et al.* (2001), and Ivanov (2001), evidence suggests that the crater production rate on Mars, averaged over 100 Myr timescales, has been constant within about a factor 2 since 3 Gyr ago (see also Neukum, 1983; Grieve and Shoemaker, 1994; Grier *et al.*, 2000). Thus, isochron crater density levels scale roughly with age after 3 Gyr ago.

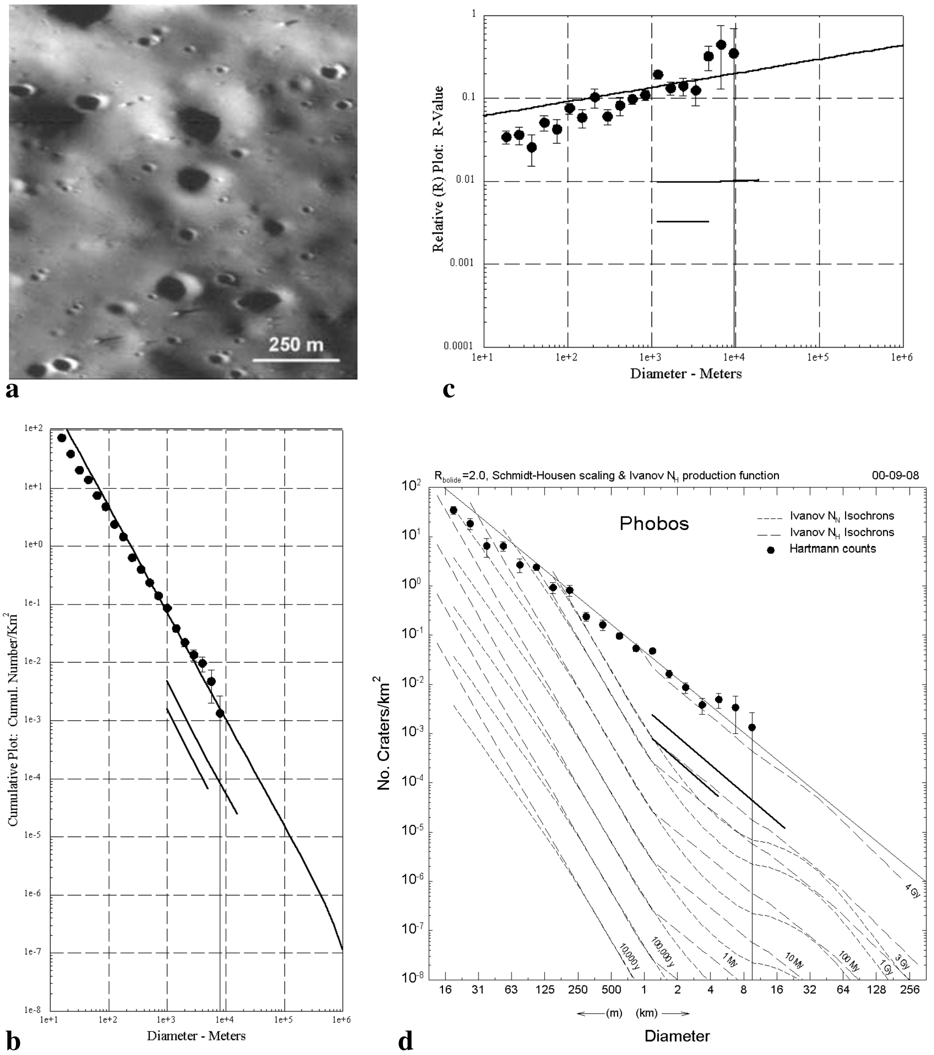

Figure 3. a) MGS image SP2-55103, showing Phobos. b-d) Crater densities on Phobos measured by Hartmann from Mariner 9, Viking, and MGS imagery, plotted in the three formats of Figure 2. The solid line is the least squares fit by Hartmann (1984) to the most densely cratered surfaces on the lunar far side, Phobos, and outer solar system satellites, and is regarded as the empirical upper limit due to saturation equilibrium. Note contrast with Mars data in other figures.

Note that because we start with the lunar mare crater densities (Ivanov, 2001), the Mars isochron positions depend fairly strongly on the age assigned to the lunar maria, because the cratering rate was changing during that time. Table I summarizes this issue by tabulating the total accumulated number of craters on a 3 Gyr surface, relative to various other ages, assuming Neukum's cratering time dependence and, for comparison, a constant cratering rate. The table shows how the

TABLE I

Crater Density at 3000 Myr Relative to that on Older Surfaces

Assumed age of lunar mare surface, *T*	[Crater density on 3000 Myr surface]/[Crater density on surface of age *T*]	
	Neukum time dependence	Constant cratering since *T*
3400 Myr	0.68	0.88
3500 Myr	0.54	0.86
3600 Myr	0.38	0.83

assumed mean mare age affects positioning of the 3 Gyr isochron (and hence all the isochrons for younger ages). We adopt Ivanov's mean age of 3.4 Gyr and multiply Ivanov's Mars crater densities at 3.4 Gyr by 0.68 to get the position of the 3 Gyr isochron. To be conservative, we estimate a 20% uncertainty in ages introduced in this stop. While Figure 2 shows the Ivanov/Hartmann/Neukum 3.4 Gyr isochron, because it is represents our initial input data, the remaining figures in this paper show the 3.0 Gyr isochron for ease of interpolation; it has a slightly lower position.

4. Young Surfaces: Evidence for Youthful Volcanism

As emphasized by the MGS Imaging Team, it is important to study the youngest Martian volcanic stratigraphic units for several reasons. First, their dates constrain models of geothermal evolution of the planet. Second, a deep, youthful lava flow, if unaltered by still more recent dunes or dust drifts, is a perfect surface for recording the production function diameter distribution of impact craters, and offers a test of our assumed production function shape (i.e. isochron shape). Third, as noted by Hartmann (2001), youthful volcanism might provide a key to understanding recent aqueous phenomena, such as young water deposition and erosion features (Shih *et al.*, 1998; Swindle *et al.*, 2000; Sawyer *et al.*, 2000; Bridges and Grady, 2000; Malin and Edgett, 2000a), by providing a geothermal source for melting permafrost. We now discuss several examples of young lavas.

a) Arsia Mons. This volcano was studied by Hartmann *et al.* (1999) in one of the first MGS reports on young volcanism, where ages of 40–200 Myr were suggested in the summit caldera. Figure 4a shows a sample MGS image of the young lava textures along the rim of the summit caldera. Figure 4b-d shows our current data set and the isochrons diagrams derived here. The data in the caldera give a best fit to a mean lava flow age in the central caldera of about 200–400 Myr, with a somewhat older, less constrained age of about 500–2000 Myr for the average of the whole volcano surface flows, based on larger craters.

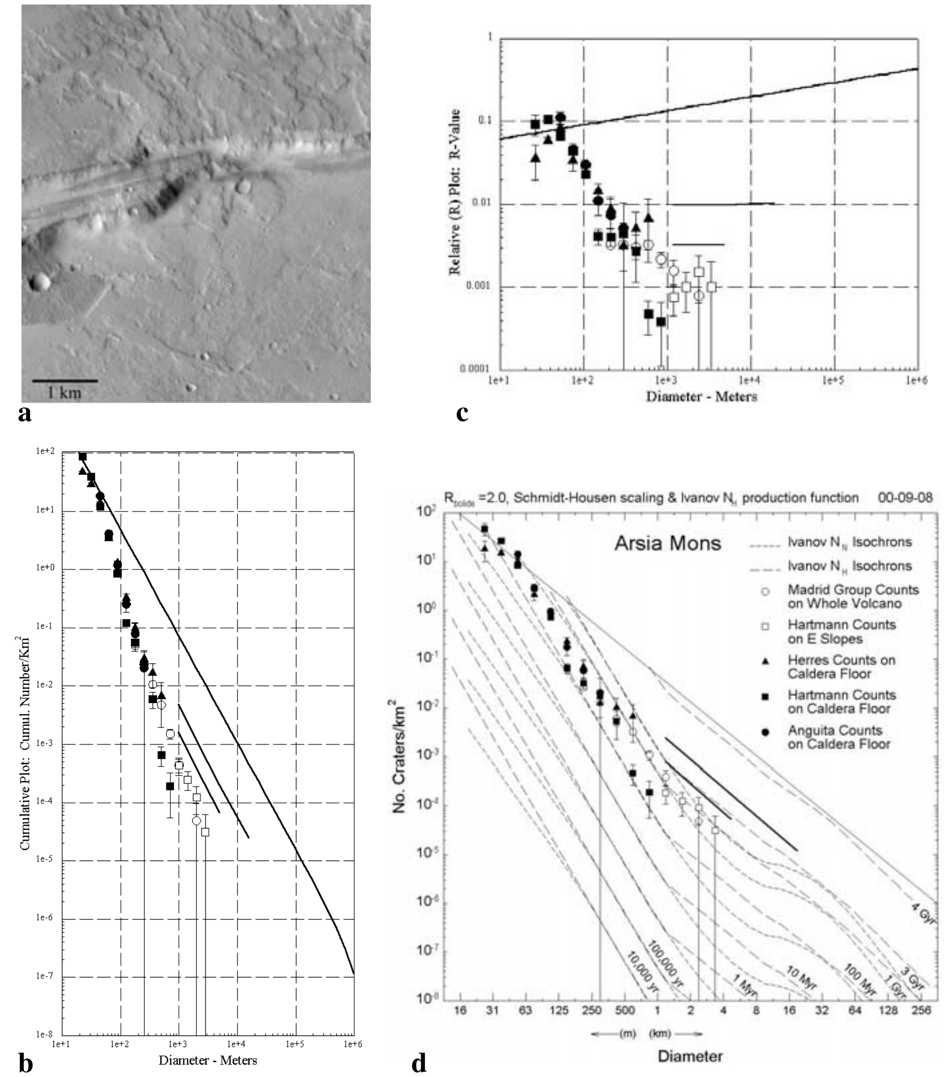

Figure 4. Young lavas on Arsia Mons. a) The outer rim of the Arsia Mons caldera (*top*) and the caldera floor (*bottom*) show overlapping young lava flows. (Lat. 8.7 S, long. 120.8 W, MGSAB1-03308). b-d) Comparison of crater counts and isochrons derived in this paper suggests a characteristic age of a few hundred Myr for most surface flows on the flanks and caldera floor of Arsia Mons.

b) Elysium Planitia. This area was correctly described as young lavas by Plescia (1990). Keszthelyi *et al.* (2000) confirmed unusually fresh-appearing lava textures, similar to examples of flood basalts found in Iceland. Hartmann and Berman (2000) derived an age of a few Myr to 100 Myr from crater counts. Figure 5a shows MGS images of young lava flows at different scales. Figures 5 b-d along with plots of the crater counts against the isochrons derived here. These data at $D < 500$ m suggest very young ages of a few to 30 Myr for some of the youngest flows.

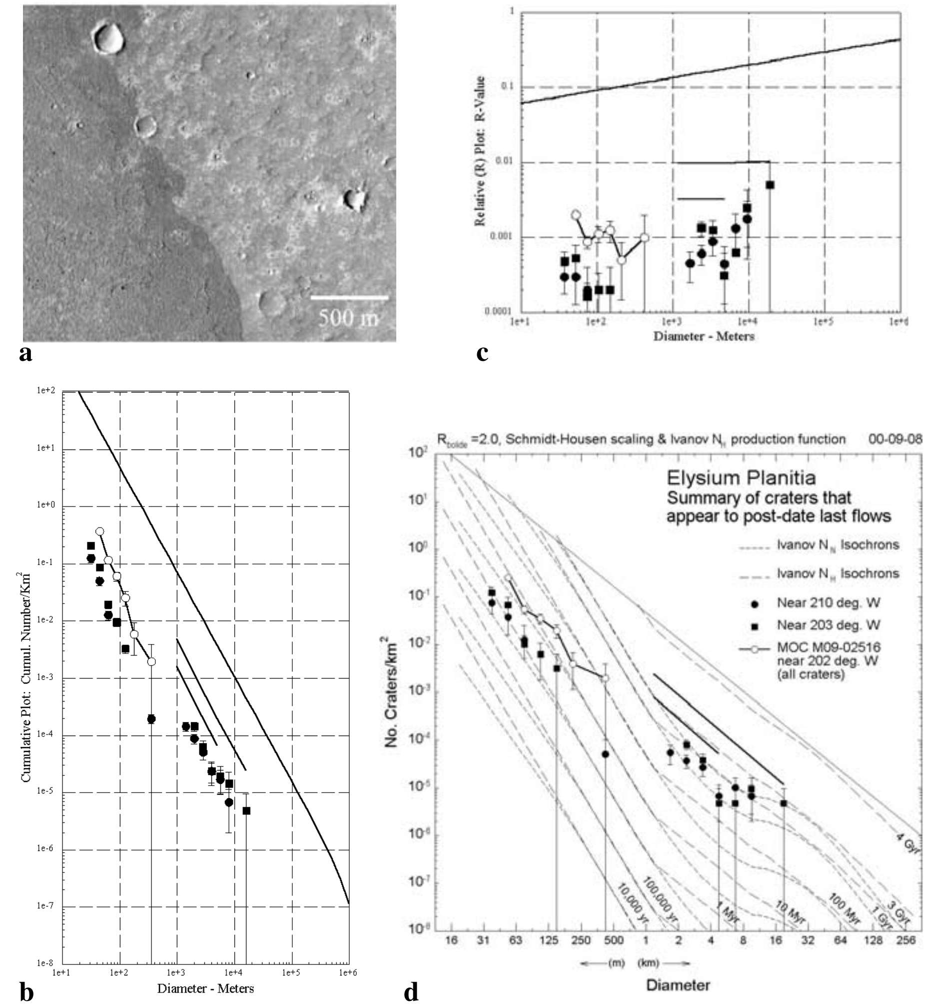

Figure 5. Young lavas in Elysium Planitia. a) Younger, darker flow (*bottom*) flows across an older, cratered surface and around the largest crater. (Lat. 5.5 N, long. 214.3 W, MGS MO3-03779). b-d) Crater counts reflect heterogeneity, with some older background flows having ages of order 900 Myr, while some of the youngest lava flows suggest ages of 10 Myr or less.

Hartmann and Berman (2000) raised an important point about the dating of the Martian lava plains. While the lunar mare lavas date almost entirely from 2.9 to 3.9 Gyr, or at most from around 2.0 to 4.0 Gyr (a factor of 1.3 to 2.0 in age), the Martian lavas, even within a restricted area such as Elysium Planitia, appear to cover a much larger range in age, because the youngest flows are so young. Thus, if the Martian flow ages in Elysium Planitia range from 10 Myr to 300 Myr, their range of crater densities spans a factor 30, rather than the factor mentioned for the moon. For this reason, individual high resolution MGS images which happen to fall in the youngest individual flows can fit much younger isochrons than the average crater densities at larger diameters, derived over larger areas from low-resolution Viking images. This effect can cause some difficulty in fitting crater density data to our isochrons, with some MGS frames giving much lower ages at low diameter ($D \lesssim 500$ m) than at high diameter ($D \gtrsim 1$ km). However, we note that individual flows shown on individual MGS frames fit our isochrons reasonably well, as seen by the connected dots in Figures 5b-d.

c) Amazonis Planitia. Amazonis Planitia is a region northeast of the young Elysium Planitia lavas, which appear to flow into the Amazonis area (Plescia, 1990; Keszthelyi *et al.*, 2000). Figures 1a and 6a show aspects of the area, including a very uncratered flow overlapping a young background. As shown in connected dots in Figure 6b-d, some of these sparsely cratered flows fit the Neukum and Hartmann isochrons for ages as young as 3 to 20 Myr. Our average of data over the older background flows (*solid symbols*) gives a fairly good fit to the Neukum and Hartmann isochrons for age $100-200$ Myr, all the way $D = 31$ m to $D = 1$ km. At larger sizes, $D > 1$ km, the isochrons suggest older ages, $\sim 500 - 900$ Myr on the Hartmann system to $0.6 - 2.0$ Gyr on the Neukum system. The 5 to 10 km craters counted on Viking frames could actually predate a few of the final, thin (4-m?), 10-Myr old flows that dot the Amazonian plains.

d) Olympus Mons. Olympus Mons is of special interest as the largest volcanic construct on Mars. Figure 7a shows an example of an individual recent lava flow running from top center to bottom center. Figures 7b-d show our various data sets. Using the Hartmann or Neukum isochrons, the data in the range $45 \text{ m} < D < 700$ m suggest a characteristic age of the order 100 to 200 Myr, respectively, for the uppermost exposed lavas on the slopes of Olympus Mons. Data including lower resolution views at $D > 700$ m suggest an older age of the order $300 - 500$ Myr for flows in the upper few hundred meters. Some MGS frames such as MGS/MOC SPO1-41105 show individual flows with much lower crater densities giving ages of the order 10 Myr in either isochron system (*connected open circles*).

5. Comment on Mid Range Ages by Crater Count Methods

Figure 8 shows the region of the Viking 1 landing site in Chryse Planitia. This area and many other plains are older than the young lava flows we have been discussing. Both isochron systems indicate ages in the range of 3 to 4 Gyr, probably involving craters formed in underlying strata, whose rims and ejecta are still exposed. The Chryse Planitia plains appear to be cut at their western edge by massive flow features, where water apparently emptied into the area.

Although we can assign older absolute ages to such plains than to the young lavas, we wish to point out a fundamental limitation of the crater count method as applied to Mars at the present level of our knowledge. The uncertainty of a factor 2 in ages, arising primarily from the uncertainty in the factor R, presents an

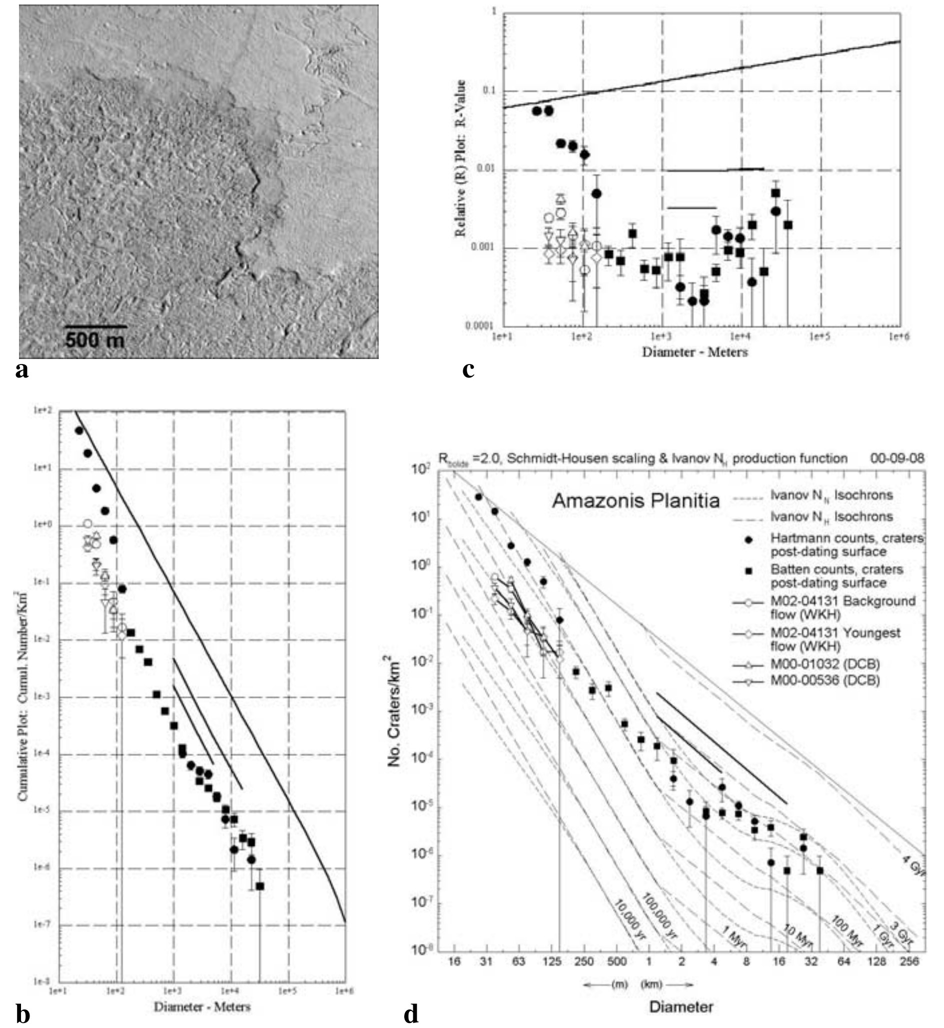

Figure 6. Young lavas in Amazonis Planitia. a) Fresh lava textures, similar to those of Figure 5a in Elysium Planitia. (Lat. 26.5 N, long. 167.5, MGS 02-04131). b-d) Crater counts suggest an average age of the order 200 Myr, with the youngest individual flows having ages as young as 10 Myr or less.

unfortunate situation for dating events in "mid-Martian" history. For example, if our best dating of a given feature is 2.0 Gyr, the actual 1-σ range of ages could be from 1 to 4 Gyr. Such an age has little value in placing constraints on the geological history or geophysical evolution of the planet. This is the reason we emphasized the youngest volcanism in Section 4. If we obtain an age of the youngest volcanic features of, say, 20 Myr, then even a 4-σ error would give an age of 80 Myr, and we would appear to have a robust constraint on geologically young volcanism.

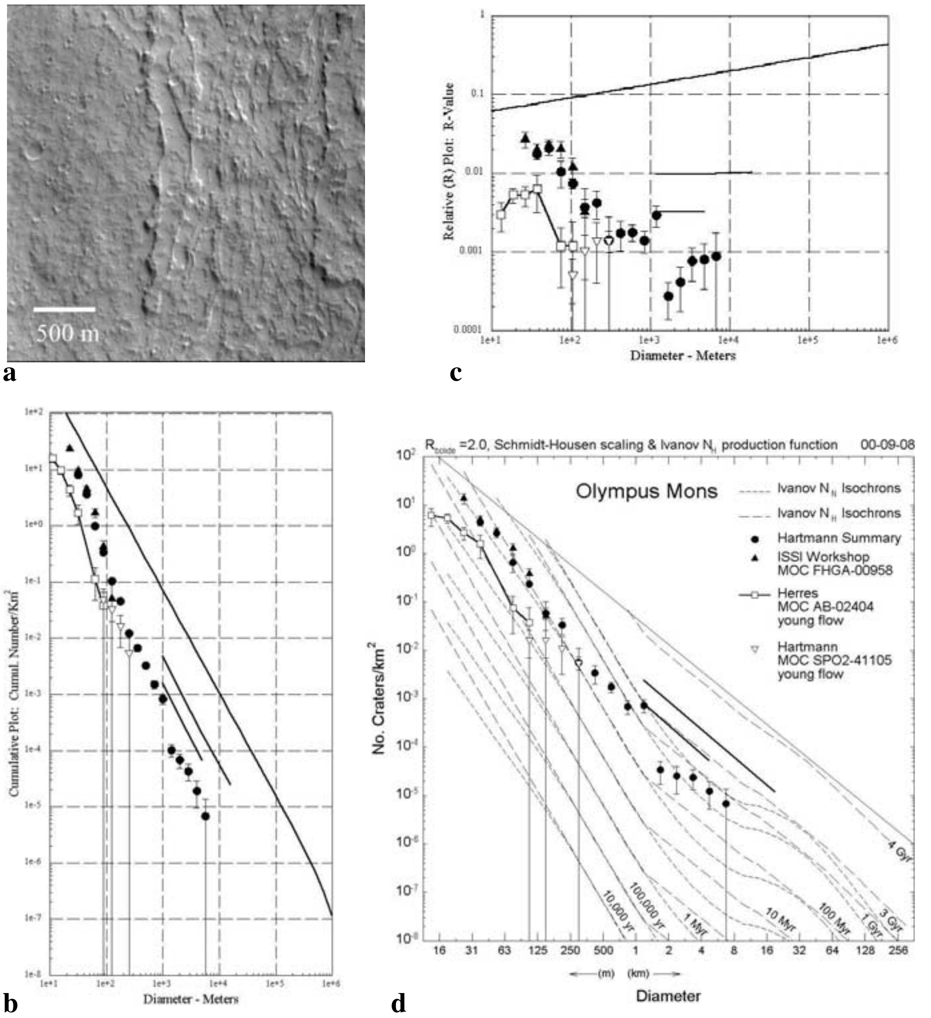

Figure 7. Young lavas on Olympus Mons. a) Tongue of lava the flank, leaving a negative relief channel with levees at the top, changing to a positive relief flow front at the bottom. Lat. 20.0 N, 133.3 W, MGS M09-05643. b-d) Crater counts suggest an average age of a few hundred Myr on the slopes, with the youngest flows having ages of the order 10 − 100 Myr.

6. Older Areas: Steady State Size Distribution and Long-term Crater Infill

Before 3.5 Gyr ago, the cratering rate was higher. Surfaces of that age approach the saturation equilibrium density in terms of accumulated impacts, but the observed numbers of craters has been reduced by cumulative effects of erosion and deposition during or since that era.

Mars Global Surveyor images affirm that mobile dust drifts and thin lava flows are a strong influence in obliterating smaller craters (Malin *et al.*, 1998; Keszthelyi

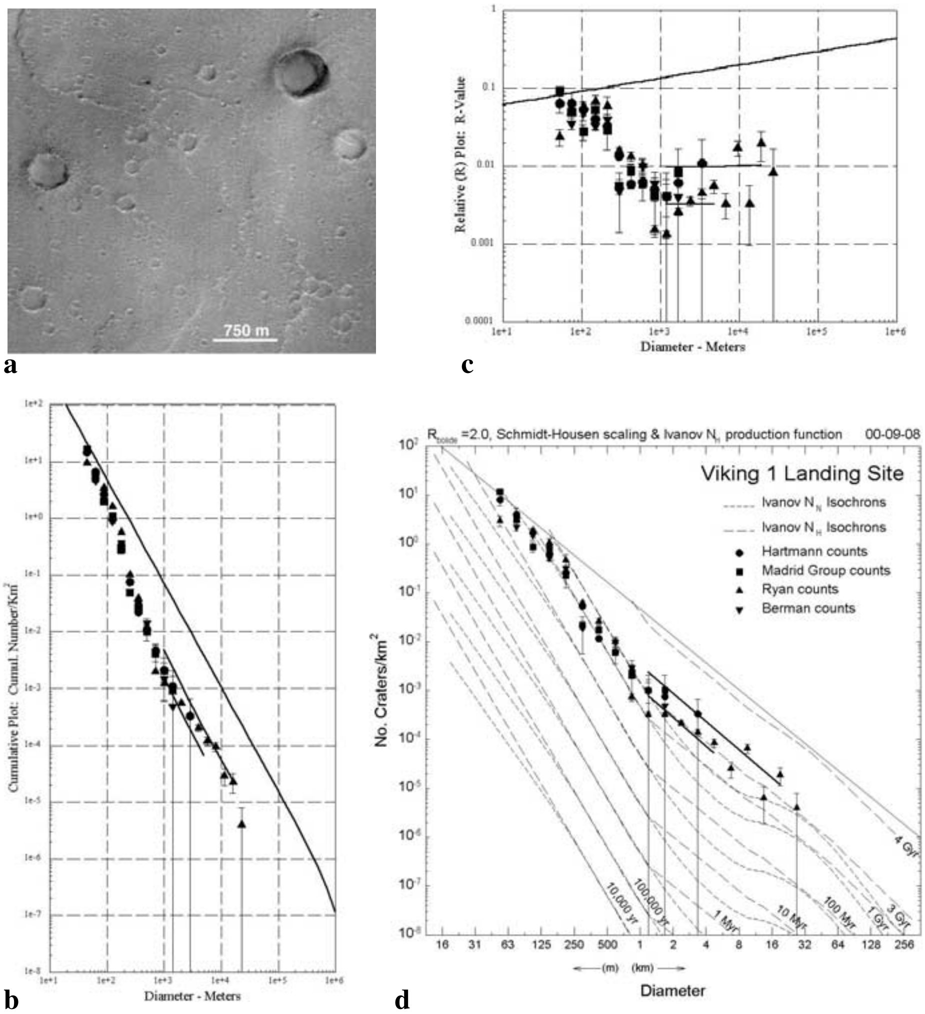

Figure 8. Viking 1 landing site area. a) Cratered plains of Chryse Planitia near the Viking 1 landing site. Lat. 22.5 N, long. 48.0, MGS SP1-23503. b-d) Crater counts suggest an age of the order 1–3.5 Gyr for the plains in this region. See text for discussion.

et al., 2000; Hartmann and Berman, 2000). Greeley *et al.* (2001) discuss the pervasive effects of aeolian deposition, and the possibility that some older surfaces have been covered and then exhumed, reducing the crater density. In principle, actual ages could thus be larger than ages derived from observed craters on such a flow.

Could such effects negate our conclusions about young volcanism? Probably not, for several reasons. 1) Even if all these areas had spent, on average, half the time buried, the derived CRA would be half the true age, which still would evidence geologically young volcanism on Mars. 2) To argue that the true ages are ∼3 Gyr, one must argue that all these areas have spent 97 − 99% of their history buried with-

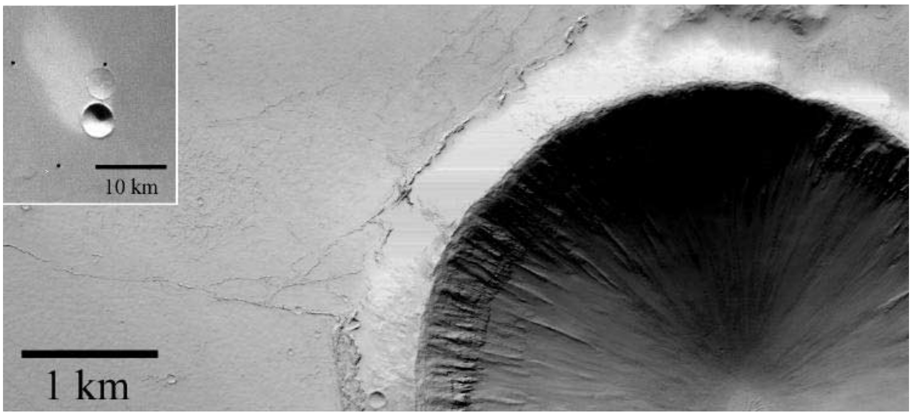

Figure 9. Young, sparsely cratered lava flows nearly covering a 4 km crater in Elysium Planitia. Thin flows have lapped up against the crater rim, and additional flows could have breached the rim and covered the interior, while leaving the rims an interiors of larger craters intact. Inset shows a Viking frame of the same crater, illustrating that crater counts on low-resolution Viking frames may include seemingly fresh craters that are actually postdated by thin lava flows that lap up against their rims or ejecta blankets, without covering them. Lat. 26.4 N, long 165.8 W, MGS M02-00364.

out accumulating craters, and that vast areas from Elysium Planitia to the summit of Arsia and Olympus Mons have been exhumed very recently. This would, in itself, require recent massive geologic activity, though not volcanism. 3) Additionally, one would need to argue that the measurements of Mars meteorite ages by different labs with different isotopic systems are seriously and systematically in error.

Averaging over large areas, mobile dust does gradually accumulate on crater floors, because they are potential wells. The net effect of dust migration and, in certain areas, continued lava flows, is to cover and obliterate smaller craters while leaving larger ones. How can we predict crater size distributions for the conditions in which mobile dust deposits and other cumulative infill processes tend to obliterate craters? The early modeling work of 1966-71, by Öpik (1966), Hartmann (1966a, 1971), Chapman *et al.* (1969), and Chapman (1974) treated crater floors as potential wells and assumed that during long term episodes of deposition and deflation, there would be a net deposition in low spots. In the first-order model, the crater was assumed to disappear when the dust infill or lava flows reached the top of the rim. MGS images also show thin lava flows lapping up against the otherwise sharply-defined rims or rampart ejecta blankets of fresh-looking bowl-shaped craters (Figure 9). If the lava reaches the top of the rim, lava would flow into the crater and partially or totally fill it, obliterating smaller craters while leaving larger craters relatively fresh-looking, at least at low resolution. If the average rate of dust deposition in crater floors, or the average rate of lava accumulation around rims, is assumed to be constant in a simple model, then the lifetime of a crater would be proportional to crater depth (or rim height, which is roughly proportional to crater depth), at least to first order.

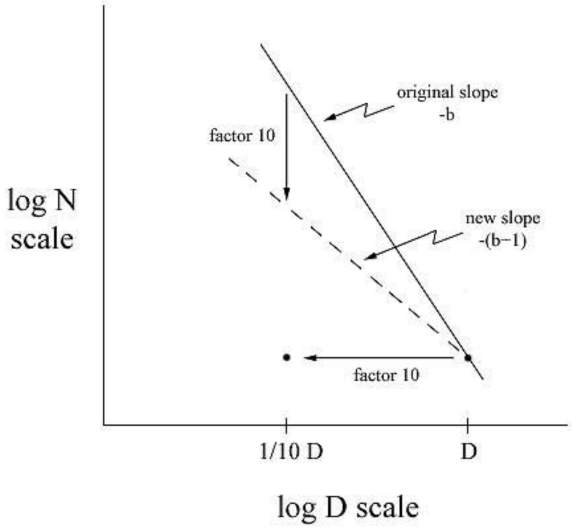

Figure 10. Schematic diagram illustrating the effect of gradual, constant crater infill in producing a steady state size distribution. If craters tend to fill in (due to processes such as net dust deposition and/or lava flows) the lifetime will be proportional to depth and rim height, which is roughly proportional to diameter D. This causes a loss proportional to D, which reduces the slope by approximately unity. See text for further discussion.

This in turn means that small crater lifetimes would be roughly proportional to their size, with small craters disappearing more rapidly, leading to a shallower slope in the crater size distribution on old surfaces. The basic idea can be understood graphically as in Figure 10. Suppose a crater of size D has depth d, and after time T it has been just filled in by dust, and the rim has been worn down and perhaps mantled by drifts, to the extent that it is not detected in crater counts. Now consider a crater of size $0.1\ D$. As a thought experiment, suppose depth is proportional to diameter, so that it has a depth $0.1\ d$. Then the oldest small craters would be 1/10 as old as the oldest big crater. If we assume constant crater production, we would see only 1/10 of the total number that had formed. This bends the D distribution down to a shallower slope, by unity in this example, since one decade in N is lost for one decade decrease in D. Chapman *et al.* (1969) and Hartmann (1971) made similar analyses, and Hartmann (1999) modified it with better data on the depth-diameter relation. The latter curve is used here. To be more realistic, if a proportionality exists between the a declining cratering rate and a declining infill/obliteration rate during the first 1 Gyr, then a similar shape of curve still results (Hartmann, in preparation). This predicted behavior fits surprisingly well with observed data, suggesting that the older regions of Mars have been shaped by measurable mean net infill of craters. The crater populations, in the oldest area of Mars, are dramatically different than those in younger areas or in the old, unflooded uplands of the moon

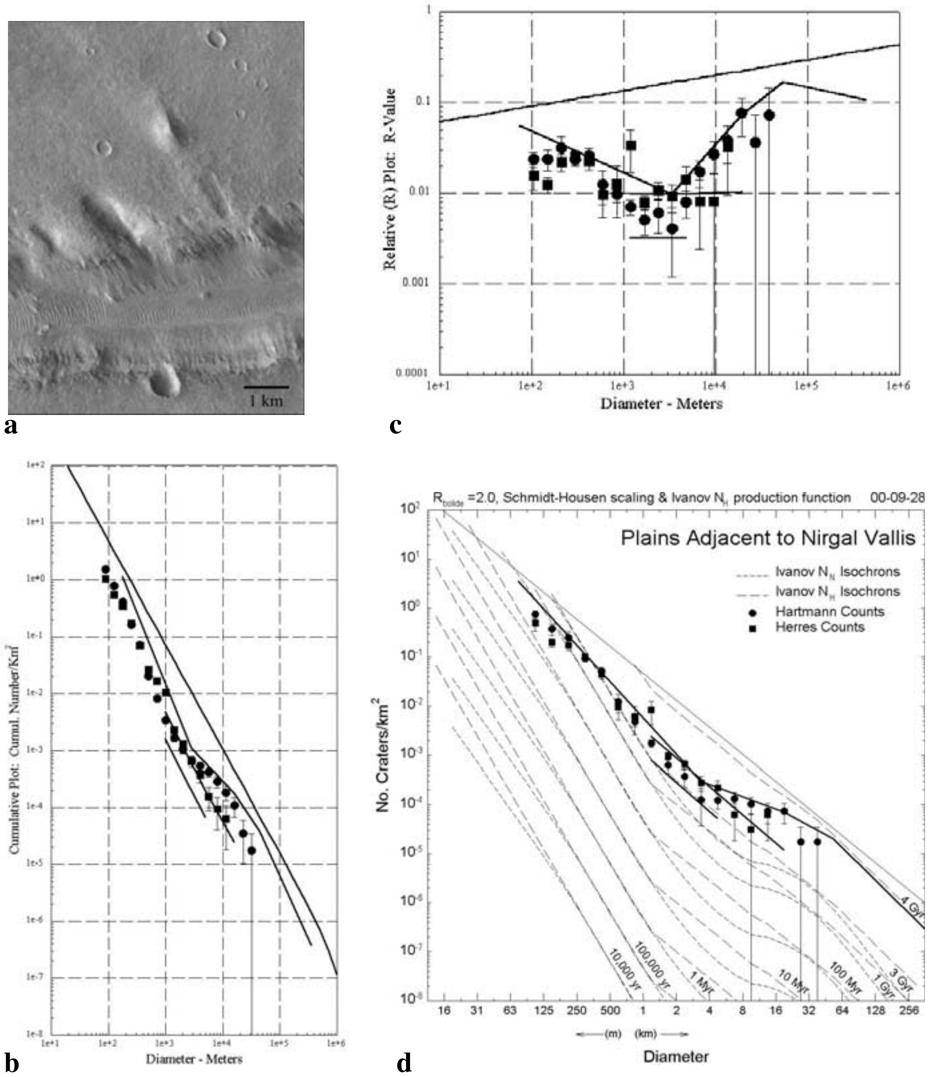

Figure 11. Plains Adjacent to Nirgal Vallis. a) Examples of degraded craters. Lat. 28.6 S, long. 41.6 W, MGS AB1-00605. b-d) Crater counts show good fit to the predicted steady state line.

(Hartmann, 1971; 1995). We now give examples of older, upland surfaces that support the principles discussed above. Hartmann (1999) gives other examples.

a) Uplands adjacent to Nirgal Vallis. An example of a moderately old Martian upland is given in Figure 11, showing the surface and crater counts around Nirgal Vallis, in the southern uplands. The MGS image shows a range of degraded morphologies with intercrater flat areas that may be covered with dust sediments. The crater counts approach saturation at $D > 16$ km, and follow the steady state deposition law derived above at smaller diameters.

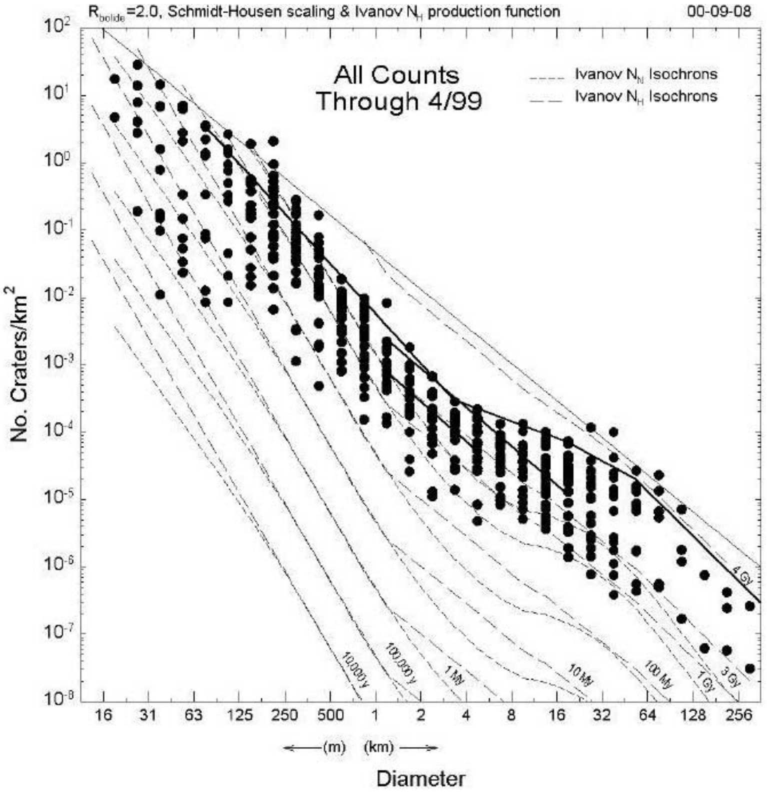

Figure 12. Potpourri of Martian crater counts on exposed Martian surfaces show a general fit to the predicted steady state line (*solid bent line*), with a scattering of many younger surface ages. A comparison is made to the Phobos counts (*top*), proving that losses must have been experienced on the Martian surface by erosion and deposition.

b) Potpourri. To demonstrate the behavior of the oldest regions, Figure 12 shows a "grab-bag" sampling of crater counts from the PSI group from many different terrains on Mars. Of great interest is the upper envelope on crater density in the oldest areas. It falls dramatically below the saturation line found for Phobos (Figure 3), but fits the profile suggested for long term infill and erasure of craters, described above. The interpretation is that the oldest craters of $D \gtrsim 22$ km are in saturation and date back to very early times. The oldest craters of 500 m$<D<$22 km have lifetimes less than the age of the planet and fall well below saturation. Still smaller craters have even shorter lifetimes, but form fast enough to maintain densities up to saturation on old surfaces. The data support the view that, under typical Martian conditions (just as in the more extreme case of Earth) erosion and deposition limit the crater densities to a steady state curve below that on the lunar highlands.

From these principles, one can estimate net mean infill rates of craters from Figures 10-12. For example, the lifetimes (maximum ages) of 350 m scale craters are of order 3.0 Gyr. These craters have depth of order 70 m (Pike, 1977; Strom *et al.*, 1992), suggesting a mean infill rate of order 20 nm/yr on crater floors, averaged over the last 3.0 Gyr. Larger craters of $D = 16$ km have lifetimes around 3.5 Gyr and depth 1300 m, giving a mean infill rate of order 400 nm/yr since that earlier time. The infill rate in the first Gyr must have been higher than the later rate, according to these numbers. A more systematic approach (Hartmann, in preparation) suggests infill rates were one to two orders of magnitude higher prior to ages around 3 Gyr ago, supporting a result in the next section. These numbers, for net deposition on crater floors, are not inconsistent with estimates of erosion. Golombek and Bridges (2000) list 100 to 10,000 nm/yr in the Noachian, 100 to 1000 in the Noachian to Hesperian, and 0.1 to 10 nm/yr from Hesperian to present.

7. Dating the Amazonian/Hesperian/Noachian Relative Stratigraphic System

A goal of Martian chronology studies is to derive the absolute dates of the relative stratigraphic periods defined by Tanaka (1986). In principle, such dating is now straightforward, because we can use Tanaka's defining crater densities to measure the ages from our isochron system. In practice there are several complications.

First, Tanaka defined the boundaries only in the diameter range 1 km$<D>$16 km, which leaves open the question of the boundaries that could be determined (for example) from MGS images at crater diameters of 11 to 500 m. Second, Tanaka assumed that the crater production function followed a -2 slope cumulative power law in this region, and calculated crater densities at $D = 1$ km and 4 to 10 km by extrapolating from densities at $D = 2$ km (Tanaka, 1986, Table 2 footnote). Current data show the production function is shallower than Tanaka's fit. This means the Tanaka assumed isochron shape does not exactly fit ours, producing a D dependence of inferred age. Worse yet, the D range of Tanaka's definitions, especially from 4 to 16 km diameter unfortunately overlaps the region where the Neukum and Hartmann systems, as reduced by Ivanov (2001), give the least consistent ages. Thus we can give only approximate ages for the boundaries. Finally, some of these approximate ages mostly fall in mid-Martian history (1 to 3 Gyr), and as explained in Section 5, these are the least valuable in constraining Martian geologic time, because of the uncertainty factor in our absolute ages, of about two.

While Tanaka's definitions of the beginnings of the epochs are precise, they are not completely internally consistent because of point 2 above, and there is a slight imprecision in defining the boundaries of the epochs. In view of this, and in view of the importance of the beginning of the Amazonian, we have re-examined the crater densities at the beginning of the Early Amazonian, fitting crater data to a wide size spectrum, not just to the diameters cited by Tanaka in the original definition. We use counts (from Neukum's group) for the Chryse/Arcadia Planitia type area of 57,500 km^2. Figure 13 shows a fit of 100 craters with $D > 1$ km to the Neukum production function derived by Ivanov (2001). The smaller craters,

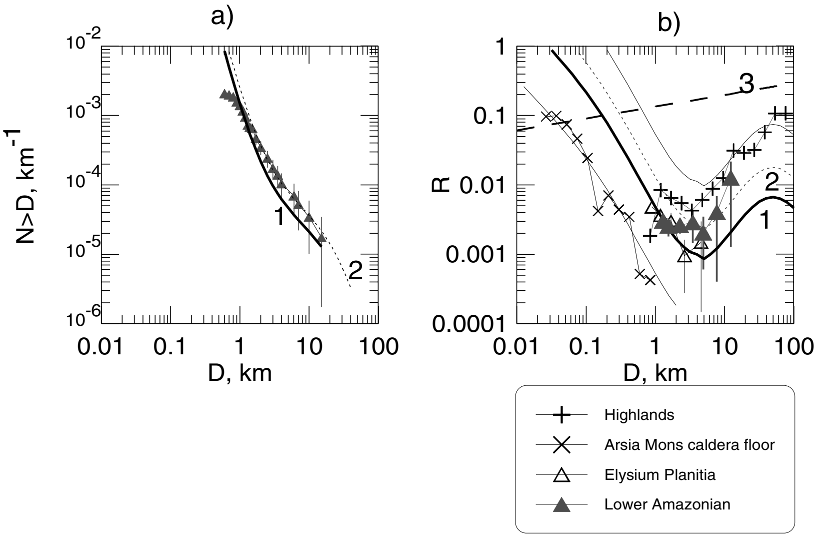

Figure 13. Crater densities in type areas related to the beginning of the Lower Amazonian, relative to Martian highlands and to Arsia Mons caldera. The fits of the Neukum production function shape to the smaller (*curve 1*) and larger (*curve 2*) craters in Chryse/Arcadia Planitia are shown. The R-plot in b) includes a surface of similar stratigraphic age in Elysium Planitia (*see text*). Curve 3 represents the saturation equilibrium level defined by Hartmann (1995) and found for Phobos (cf. Figure 3).

at $0.9 < D < 1.3$ km, fit a slightly lower isochron than the larger craters at $2.5 < D < 15$ km, as typical of our earlier results. An interpretation is that the larger-crater part of the distribution (Figure 13, curve 2) is related to a stratum which was subsequently eroded, lost craters of $D < 1.3$ km, and was later recratered to produce the population in curve 1, which would mark the base of the Early Amazonian ($\sim$3.1 Gyr in the Neukum system). It is not certain that this interpretation is correct, and whether curve 2 might be closer to the beginning of the Early Amazonian ($\sim$3.4 Gyr in the Neukum system). Neukum's group made additional counts for Elysium Planitia (Figure 13b) which give a more uniform CRA than the Chryse/Arcadia Planitia site, favoring the choice of 3.1 Gyr for the base of the Early Amazonian. This example illustrates the range of uncertainty for even a single system of isochrons, not counting the additional differences between the Hartmann and Neukum systems in the size range of $D \sim$ a few km.

Note that we make no effort here to redefine these boundaries or apply a correction to the -2 power law production function shape assumed by Tanaka. Although current data suggest a certain intrinsic "fuzziness" in the Tanaka definitions of the boundaries, we retain his definitions in terms of specific crater densities at different Ds, and then try to make the best possible estimate of the age at each boundary.

In spite of the range of uncertainties, we offer an overview of the Tanaka stratigraphy in Figure 14. As noted by Ivanov (2001) and this paper, the geologically recent (Amazonian) epochs give the most leverage on establishing the chronologic

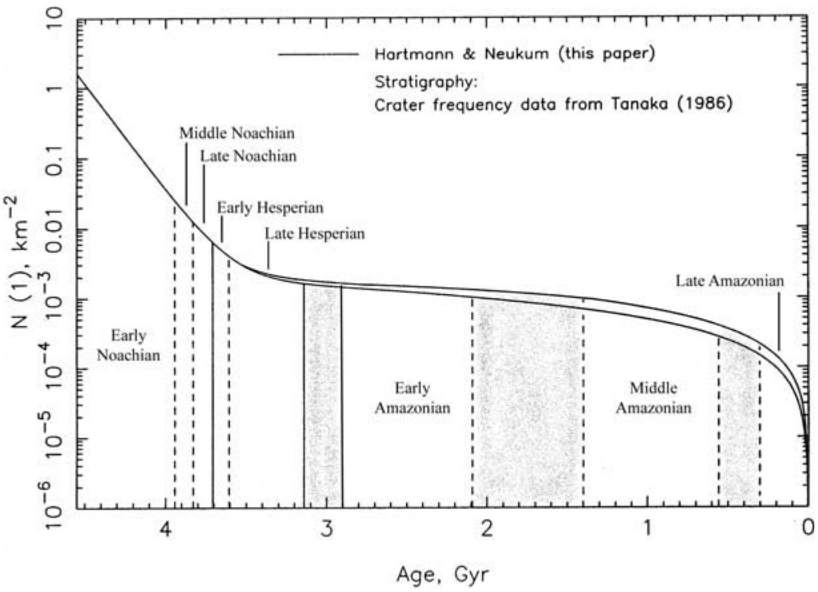

Figure 14. Mars cratering chronology model based on work in the present paper, using Tanaka's (1986) definition of stratigraphy based on crater densities at $D > 1$ km (plus our rediscussion of the definition of Lower Amazonian), and Ivanov's (2001) derivation of isochrons from Neukum and Hartmann data. The solid lines give model ages based primarily on the Ivanov-Neukum isochrons combined with the Neukum equation for time dependence of cratering (with essentially constant cratering rate after 3 Gyr ago). The left curve (older ages) is from Neukum data, the right curve (younger ages) from Hartmann. The diagram shows why uncertainties are greatest in mid-Martian histories. The model ages assume $R_{\text{bolide}} = 2.0$. Model ages younger than ~3.0 Gyr are proportional to $1/R_{\text{crater}}$ (which is roughly proportional to $1/R_{\text{bolide}}$) and thus an additional uncertainty enters for those younger ages.

system because the present cratering rate is best known, and because earlier dates crowd around 3.5 − 4.1 Gyr because of the high cratering rate at that time. To estimate ages in the Tanaka system we start with the Tanaka crater density definitions (taking into account the above discussion of the Early Amazonian beginning) and then combine these data with the Neukum equation for crater density as a function of time (Neukum *et al.*, 2001, Equation 5). We find the following results.

1. The entire Noachian Period lies before 3.5 to 3.7 Gyr ago according to both sets of isochrons. This appears to be a fairly robust result. Note that Stöffler and Ryder (2001) re-evaluated the ages of lunar basin impacts (placing all of them essentially between 3.7 and 3.9 Gyr ago. As a result their Figure 11 implies that the curve in our Figure 14 turns up much more steeply at about 4.0 Gyr than we show. We regard their age intepretations as intriguing but still unproven. In any case, they do not strongly affect our result, because the upturn is essentially within the Early Noachian. Indeed, a stronger upturn would even more tightly constrain early ages on Mars (Figure 14), because all $N(1)$ crater densities higher than ~0.005 would be forced into the age range of ~3.7 − 4.1 Gyr.

2. The boundary between Hesperian and Amazonian lies fairly early in Martian history, probably around 2.9 (Hartmann system) to 3.3 (Neukum system) Gyr ago. The position defined by Tanaka at $D = 1$ km lies very close to 3.1 Gyr ago in both systems. Figure 14 uses his definitions at $D = 1$ km. Tanaka's positions at 2 to 5 km show a somewhat greater range of age in the two systems, and this difference persists in examining younger epochs. Errors in R_{bolide} could conceivably reduce the boundary age to as little as 2.0 Gyr.
3. The beginning of the mid Amazonian lies around 1.4 (H system) to 2.1 Gyr (N system). This is the biggest discrepancy in absolute ages, occurring in mid-Martian history for reasons mentioned earlier. Errors in R_{bolide} could conceivably increase the uncertainty range to $\sim 1 - 3$ Gyr. Further reconciliation of the H and N systems, and sample return or in situ dating from this Epoch would be extremely valuable to reduce uncertainties in the system.
4. The beginning of the Late Amazonian is placed at about 0.3 Gyr (H) to 0.6 Gyr (N). Errors in R_{bolide} are unlikely to make the Late Amazonian older than 1.0 Gyr. The important result here is that Late Amazonian geology robustly is not confined to the ancient past but extends into the recent part of Martain history. (Note also that any argument for shifting Late Amazonian ages outside this range would have consequences in shifting all other ages accordingly, though the Noachian is generally constrained to before about 3.5 Gyr, due to the high crater densities, in any interpretation.)

Tanaka *et al.* (1987) used stratigraphic mapping to tabulate the total areas of Mars resurfaced by volcanism, and fluvial, periglacial, or other processes in each epoch. We divide the total area surfaced by the newly estimated duration of the epochs to calculate the rate of activity (km^2/yr) as a function of time. Regardless of whether the Neukum or Hartmann isochrons are used, the total resurfacing rates (km^2/yr) by volcanic, fluvial, periglacial, and cratering processes were all much greater in the Noachian and Hesperian before about 3 Gyr ago (Figures 15c-f). The data suggest that eolian resurfacing has continued at a more nearly constant rate. Tanaka *et al.* (1987) pioneered this analysis and obtained a similar result, but with a wider range of uncertainty in available chronological models. The modest recent upturn in reconstructed fluvial, periglacial, and cratering activity (Figure 15c-e) may result from errors in the assigned durations of recent epochs, or from the fact that the most recent units are better mapped. Measuring ages of the Martian epochs allows us to study not only geologic evolutionary processes but the nature of the Martian surface. Figure 15a shows that only modest percentage of the known volcanics (or of all units) are younger than 1.3 Gyr, raising the issue as to why 3 out of 4 (or 7 out of 8?) Martian impact sites have produced such young rocks. The problem is aggravated if one argues for older ages than we have suggested. The statistic may also mean that Martian uplands are covered by deep, gardened, loosely evaporite-cemented sediments that do not efficiently produce Martian meteorites.

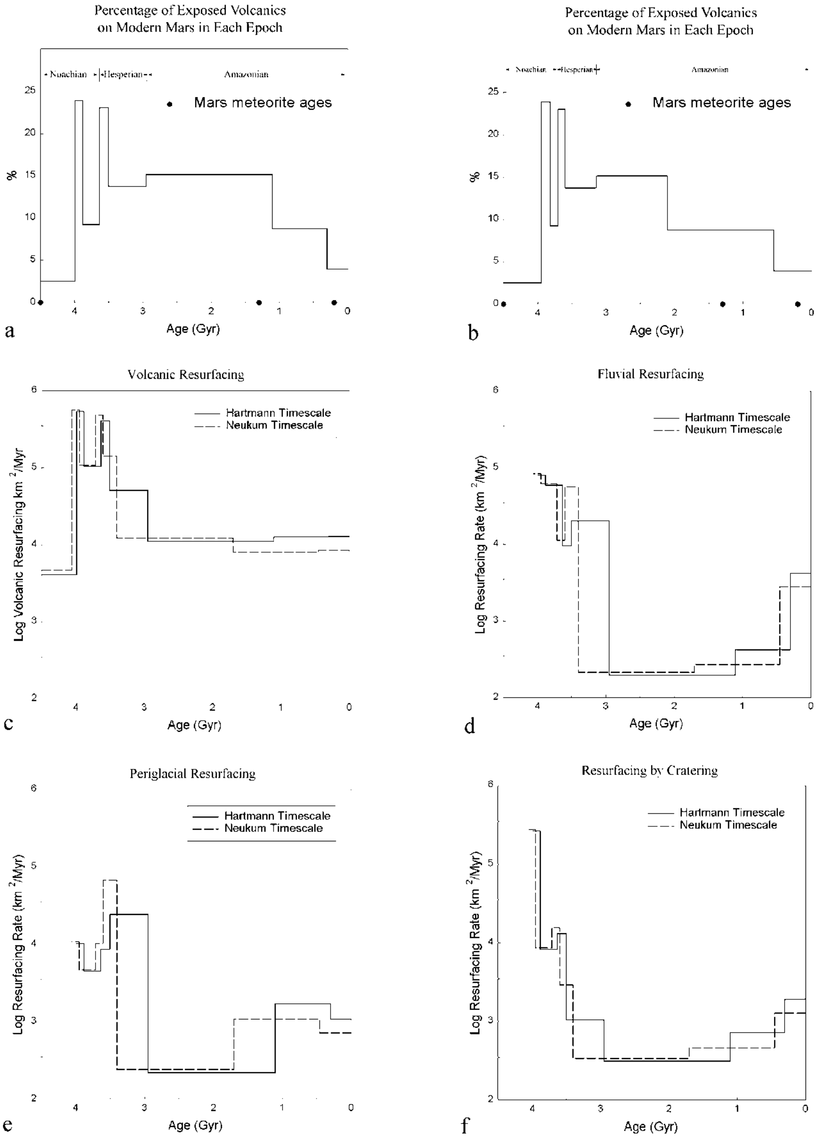

Figure 15. a-b) Age distributions for volcanic surface units on Mars, using epoch definitions and areas covered by volcanics from Tanaka *et al.* (1987), and dating systems of Hartmann/Ivanov (a) and Neukum/Ivanov (b). The two results are similar, and consistent with existence of young Martian SNC's. Larger numbers of Martian meteorites might allow a test of whether this age distribution applies, or whether ancient upland surfaces of 2 to 4.4 Gyr age are too weakly consolidated to produce meteorites. c-f) Time distributions of rate of volcanic, fluvial, periglacial, and impact resurfacing activity, based on Tanaka *et al.* (1987). Ages of epochs are drawn from Hartmann and Neukum systems (reduced by Ivanov, 2001), but slightly different from Figure 14, because of using broader diameter ranges to define the epochs. The data robustly show higher rates of activity by one or two orders of magnitude before ~3 Gyr ago. With less certainty, the data raise the possibility of increased fluvial and perhaps other activity within the last few hundred Myr, though this may merely reflect easier identification of younger features.

8. Conclusions: Implications for Martian Geological History

We have shown that cratering data offer a valuable complement to Mars meteorites in understanding the absolute chronology of Mars. Meteorites give precise dates from a few (unknown) stratigraphic units, while crater data give rough dates from all stratigraphic units. With modern understanding of orbital dynamics and impact rates, crater counts provide dates with an total uncertainty that we estimate at a factor 2. Sample return or in situ dating would calibrate the crater dating and thus vastly improve planet-wide dating.

The combination of rock and crater data offers the following view of Martian history. Crustal rock units formed as long as 4.5 Gyr ago, as evidenced by ALH84001. The fact that one of the first dozen Mars rock samples is of this age, whereas such rocks are relatively rare from lunar samples, suggests that the Martian situation is very different from the that on the moon. Crater densities indicate that the old highlands should have been gardened to a depth of a kilometer or so, but the apparent aqueous weathering and carbonate deposits in ALH84001 at 4 Gyr ago, combined with the evidence for early fluvial resurfacing and for river and lake formation on Mars (Malin and Edgett, 2000b) suggests that any early megaregolith was subject to aqueous activity and probable cementing by carbonates and salts. The exposed megaregolith crustal units dating from about 4.4 to 3 or even 2 Gyr ago, being less consolidated, sedimentary-rich materials, may produce fewer meteorites, or fewer recognizable meteorites, than the primordial crust or the young volcanic units. This may explain the “missing meteorites” in the 1.3 Gyr to 4.5 Gyr age range. Both the Mars meteorite collection and the crater counts give strong, independent lines of evidence that volcanic and fluvial activity continued throughout Martian history into recent times. At least two impact sites on Mars have produced rocks with crystallization ages of 1300 and about 170-300 Myr ago. MGS images show extremely fresh-looking lava flows with crater count ages less than 100 Myr, and possibly as low as 3 to 10 Myr. Mars meteorites and MGS images also suggest sporadic ongoing aqueous activity. Aqueous alteration in nakhlites has been dated at 670 Myr ago. Virtually uncratered hillsides have apparent aqueous seep features that are much younger. Our understanding of Mars must allow for relatively recent volcanic activity and water mobility.

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