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Possible long-term decline in impact rates
1. Martian geological data

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Abstract

Quantin et al. [Quantin, C., Allemand, P., Mangold, N., Delacourt, C., 2004a. Icarus 172, 555–572] tabulated crater count data for 56 landslides along the walls of Valles Marineris. Under the assumption of a constant cratering rate after about 3 Gyr ago, as used in the 1999–2005 iterations of the crater chronology isochron system of Hartmann, and in the Hartmann and Neukum system, these data indicate a regularly increasing rate of landslides, which would be difficult to explain. We suggest that these data may support a decline in inner Solar System cratering rates by about a factor of 3 since 3 Gyr ago, not unlike predictions based on asteroid belt collision models. Such a decline is also supported by our review of data on lunar impact melts and glass spherules in a companion paper [Hartmann, W.K., Quantin, C., Mangold, N., 2007. Icarus 186, 11–23]. Such models produce not only a more uniform rate of landslides over the last 3 Gyr, but also a more uniform rate of resurfacing processes which also had an apparent increase under the assumption of a constant cratering rate.

Keywords: Cratering; Mars, surface

1. Introduction

Crater population studies allow determination of the relative ages of the main geological units of planetary surfaces. Since the crater density on the Moon has been calibrated with absolute ages from Apollo and Luna lunar samples, the lunar crater chronology allows us to make rough measurements of absolute ages (Hartmann, 1970; Neukum and Ivanov, 1994; Neukum et al., 2001; Stöffler and Ryder, 2001). In terms of cratering rate, the lunar chronology highlights an intense decreasing cratering rate before 3.5 Gyr corresponding to the late heavy bombardment and a more constant cratering rate after about 3.0 Gyr. Since the Apollo/Luna samples are mainly older than 3.2 Gyr, the impact history before 3.2 Gyr is the more constrained part of the curve. The cratering rate after ∼3.0 Gyr has been estimated to be constant within a factor of 3, with some studies suggesting a slight decline, and others, a slight increase (see review by Neukum et al., 2001).

The lunar absolute chronology has been transferred to Mars taking into account the proximity of Mars to the main asteroid belt, the martian gravity and also the effect of the martian atmosphere (Hartmann, 1966a, 1999, 2005; Neukum and Wise, 1976; Neukum et al., 2001; Ivanov, 2001; Hartmann and Neukum, 2001). According to all the error sources, the martian absolute ages for a good sampling of craters (over almost 5 orders of magnitude in diameter) are thought to have uncertainties of about a factor 2 to 4 (Hartmann and Neukum, 2001; Hartmann, 2005). Even with such uncertainties, the martian chronologic system is useful to date the geological and climatic history of Mars, because it appears to span at least three orders of magnitude in age (Hartmann et al., 1981; Head et al., 2001). Glacial, volcanic and fluvial activities have been studied by these methods which highlight that Mars, in contrast to the Moon, is a planet with some processes (volcanism, limited fluvial activity) active in the last few percent of

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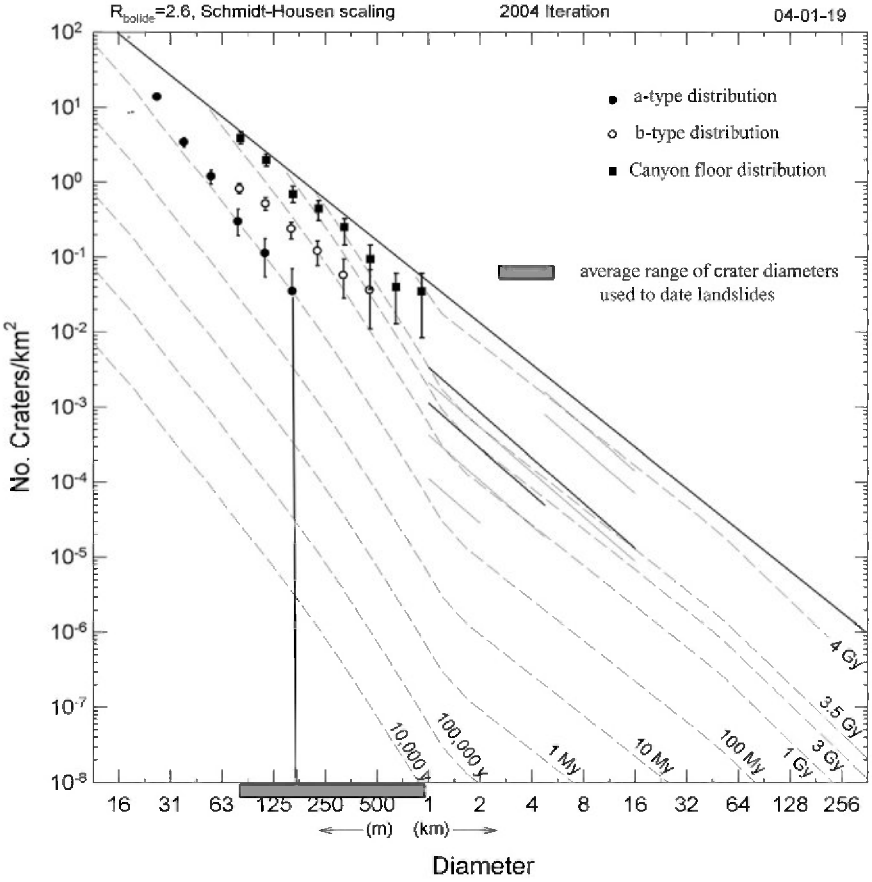


Fig. 1. Hartmann' isochrons (Hartmann, 2005) used to date landslides. A-type distribution (landslide case No. 7; Quantin et al., 2004a) is an example of crater size distribution on landslide following isochron slope. B-type distribution (landslide case No. 8; Quantin et al., 2004a) is an example of a crater size distribution on landslides crossing the isochrons. The two cases indicate different geological histories. Canyon floor distribution is given to have a temporal marker (canyon floor case No. 59; Quantin et al., 2004a).

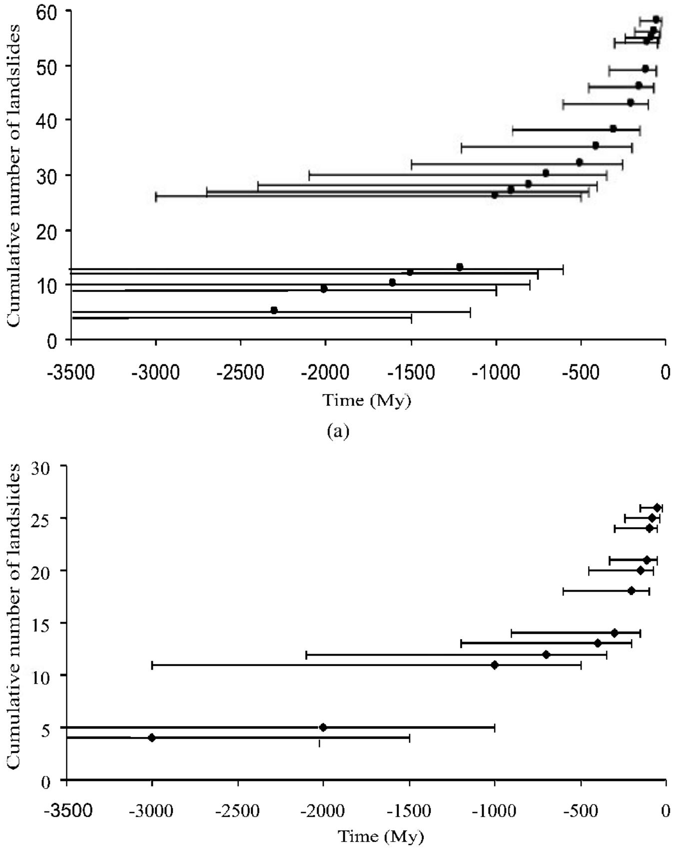
martian geological time (Hartmann et al., 1999; Neukum et al., 2004), a conclusion supported by studies of martian meteorites (i.e., Nyquist et al., 2001).

In the same way, landslides of Valles Marineris have been dated revealing activity spread over the last 3 Gyr (Quantin et al., 2004a). The landslides are thus processes that record the last 3 Gyr of impact history. Studying the landslides time-distribution, Quantin et al. observed an unexpected increasing frequency of landslides with time (Quantin et al., 2004a). The goal of this paper is to study in detail the different hypotheses that could explain this trend. After critiquing scenarios in which the ages are accepted as exact, we will study the possibility that the landslide time-dependence can be used to study the assumptions of the cratering chronology system, especially the model of constant cratering rate over the last 3 Gyr. We will detail this assumption and discuss its relevance and its consequences for the martian chronology.

2. Landslide time-distribution

Valles Marineris is affected by about 60 known landslides. These landslides are mainly revealed as thin and widespread debris aprons whose surfaces record the impact history since landslide formation. With the high resolution images from Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) narrow angle images (Malin et al., 1992), and from Mars Odyssey THermal Emission Infrared System (THEMIS) images (Christensen et al., 2004), detailed coverage of individual Valles Marineris landslides is available, allowing study of the crater population of each landslide. Quantin et al. (2004a) reported these crater populations in a histogram plotting incremental number of craters vs square root 2 diameter bin (Hartmann's representation; Hartmann and Neukum, 2001). This graphical representation allows us to plot the crater size distribution of a crater population and to compare it with theoretical crater size distributions of given ages, namely isochrons (Hartmann, 1999, 2005; Hartmann and Neukum, 2001). Quantin et al. (2004a) used Hartmann's 2002 update of isochrons, which is a refined iteration (altered mostly at crater diameter $D <$ 200 m) of the Hartmann and Neukum age model (Hartmann and Neukum, 2001; Lane et al., 2003; Quantin et al., 2004a).

Crater size distributions of 56 landslides have been established and ten canyon floor crater size distributions have been measured in order to have temporal reference (Quantin et al., 2004a). Two kinds of distribution have been observed. In the first distribution, all the points follow the isochrons (a-type, Fig. 1; landslide case No. 7; Quantin et al., 2004a). In this case, the model age of the formation was unambiguously de-



(a)

(b)

Fig. 2. Cumulative landslide time-distribution: (a) including the 56 landslides dated in Quantin et al. (2004a) including only the 26 best quality age determination, namely age determined with a crater size distribution following the isochron slope at least for 3 crater diameter bins.

termined, according to the specific iteration of the isochron system. The second case corresponds to the crater distribution whose slope is lower than the isochrons (b-type, Fig. 1; landslide case No. 8; Quantin et al., 2004a). This distribution indicates smaller craters are being lost, relative to the isochron "production function" of craters. It implies a constant refreshing process (such as deposition, regular infill, or other processes) in which the small craters disappear more quickly (Hartmann and Neukum, 2001). In that case, the point corresponding to the largest craters was used to determine a minimum age of the object. This case concerns 15 landslides (Quantin et al., 2004a). There is no particular spatial distribution of the first or the second kind of distribution. Some curves indicate an a-type segment at larger sizes, and a b-type segment at smaller sizes, in which case the steep a-segment indicates the age. The ages of the 56 landslides range from 3 Gyr to 100 Myr. Even if approximate, such ages indicate a wide temporal distribution of landslide activity, spread over the last 3 Gyr (Quantin et al., 2004a). With the 56 landslide ages, the distribution of the landslides with time has been studied. The frequency of the landslides was plotted as the cumulative number of landslides vs the time (Fig. 2) in order to take into account the minimum ages measured with a crater count distribution of b-type (Fig. 1). The curve appears exponential, implying that the rate of landslide occurrence increases with time.

3. Hypotheses to explain the curve

Why would the rate of landslides in Valles Marineris increase over 3 Gyr? In this section, we offer some hypotheses to explain the curve: These include hypotheses of real increase in landslide rate, the erasing or hiding of the oldest landslides, the effect of the quality of the age determination, the effect of using <1 km impact craters, the influence of secondary craters, and the possibility of a change in the impact flux rate.

3.1. "Geological" explanation

If the dates are correct, the temporal distribution of the landslides implies a regular increase of landslide occurrences with time. The trend then has to be interpreted in term of geological triggering factors, and this is hard to explain. The plausible candidate factor for initiating the landslides is impact cratering—or tectonic-related seismic activity (Lucchitta, 1979; Quantin et al., 2004a). For the case of landslides triggered by impact, we expect a constant trend of landslides because the cratering rate has been assumed to be constant in the dating system, over the activity period of the landslides. For the hypothesis of tectonic related seisms, we would generally expect a decreasing trend during martian history. Although there is evidence a late tectonic activity in Valles Marineris (Lucchitta, 1979; Quantin et al., 2004a), the geological record of the tectonic activity in the broader area shows major activity at the time of Tharsis bulge formation and then a decrease of the active processes (Scott and Tanaka, 1986; Banerdt et al., 1992; Golombek et al., 1992; Dohm and Tanaka, 1999; Anderson et al., 2001). Neither a major increase in cratering nor an increase of the tectonic processes by a factor >3 over the last 3 Gyr is expected on Mars.

3.2. Observational biases

Could the curve result from biases due to more difficult detection of old landslides—i.e., could the landslide time-dependence express that the oldest landslides are harder to detect than the younger ones? That could be the case if old landslides have been erased or hidden. Landslides, however, are very imposing morphologies with deposits ranging around 1000 km^2 for the average area, around 36 km for their average length and around 800 km^3 for their average volume (Quantin et al., 2004b). In addition, landslide scarps create embayment on the order of 30 km in the plateau surrounding Valles Marineris walls. Only very active processes are able to erode or to cover these huge features. In addition to the dating of landslides, Quantin et al. dated the canyon's floor adjacent to the landslides (Quantin et al., 2004a). *The floor is always measurably older than the oldest landslides*, with ages around 3.5 Gyr, corresponding to the early history of Valles Marineris. This means that no major processes occurred after ~3.5 Gyr in Valles Marineris which where able to erase the impact record of the canyon floor with the exception of sand sheets and dunes which blanket part of the floor.

Landslides thus appear to be the main active processes over the last 3 Gyr within Valles Marineris (Quantin et al., 2004a). The only processes able to hide old landslides are the landslides themselves. Landslides are randomly located along the walls of Valles Marineris and each time correspond to deep embayment. The only way to hide old landslides would be that the youngest landslides reactivated exactly the same embayment and always covered the old deposits. We have not seen any evidence of such a scenario. On the contrary, we can clearly identify the oldest landslides in case where overlapping landslides occur. For instance in Gangis Chasma, a young landslide overlaps two 3–3.5 Gyr old landslides. We have no difficulties observing the oldest landslides because: (1) the landslide scarps are intact and distinct, and (2) the younger, overlying landslides do not completely cover the older, underlying landslides, allowing the crater densities of the latter to be determined (Quantin et al., 2004a).

3.3. Methodological biases

Is there a systematic bias in our counts? In order to test this hypothesis, we made a second selection of landslides that represent only the best constrained ages. We kept only crater distributions which follow the isochrons over at least more than 3 crater diameter bins, rejecting the ones where we could obtain only a minimal age (b-type in Fig. 1). We observe that the 26 landslides with the best constrained ages display exactly the same exponential shape as the full 56 landslides (Fig. 2b). The shape of the landslide time-dependence thus appears independent of the quality of the age determination.

3.4. Influence of small (secondary?) craters for age determination

The crater diameters used to determine landslides age range from 100 m to 1 km. The reliability of the chronology in this diameter range is controversial (McEwen et al., 2005; Bierhaus et al., 2005). The issues especially concern the slope of the crater size distribution. In the original crater size distribution on the Moon, this part of the isochron was not well constrained because, even in the youngest lava plains, the smallest impact craters (the total curve of primaries plus secondaries) are in saturation. On Mars, some areas are so much younger that this part of the curve is not in saturation, and researchers such as Neukum (1983), Hartmann (2005), Neukum and Ivanov (1994), and Hartmann and Neukum (2001) estimated the production function at these diameters. Whereas the slope of the distribution for craters larger than 1 km is −1.8 (Hartmann et al., 1981), the branch corresponding to the smallest impact craters (primaries plus secondaries) is steeper (Shoemaker, 1965; Hartmann, 2005). The slope of this part of the curve was estimated at −3.8 in the 1999 Hartmann's update (Hartmann, 1999), but shallower than that in the latest update Hartmann (2005). Comparing the crater size distribution and the size distribution of the assumed impactors, Bottke et al. suggest that the expected slope for craters smaller than 1 km would be as shallow as −1.8 and secondary contamination has raised it to −3.8 (Bottke et al., 2005a). McEwen et al. (2005) recently studied the distribution of the secondary craters associated with 10-km-diameter Zunil crater, an Amazonian impact crater. They found from numerical simulations that the slope of the crater size distribution of secondary craters is very steep with value around −4.6. These simulations suggest that if the entire population of small impacts on Mars were secondaries, their slope would be steeper than we observe. In any case, the intermediate slope is probably a mixing of both primaries and secondary craters, as suggested by many authors (i.e., Hartmann, 2005; Bottke et al., 2005b). Taking into account the effect of the martian atmosphere on the crater distribution at small size (Popova et al., 2003), Hartmann's latest update refines the slope to −2.9 for crater smaller than 100 m and to −3.4 for crater between 100 m and 1 km (Hartmann, 2005).

Table 1

Slope comparison between Hartmann's isochrons, secondary distribution and average slope of crater size distribution on landslides

	Slope <100 m	Slope 100 m < > 1 km
Hartmann update 2005*	−2.9	−3.4
Secondaries**	−4.6	
Landslides***	−3.1 (±0.55)	−3.31 (±0.3)

* Hartmann (2005).

** Calculated from the predictions by hydrodynamic simulation of McEwen et al. (2005). Diameters of the secondaries of Zunil crater range below 100 m.

*** Obtained by rate mean square on the 26 best constrained crater size distribution (from Quantin et al., 2004a). The error bar corresponds to the standard deviation.

McEwen et al. (2005) conclude that the uncertainty of age determinations from small craters is too large to be reliable due to secondaries. The authors suggest that the landslide time dependence of Quantin et al. (2004a) could be explained by this effect. We have two main rebuttals to this issue. To address the effect of inappropriate slope at small diameter in the reliability of landslide age, we computed the average slope for a different part of the crater size distribution on landslide. For the few distributions showing impact craters larger than 1 km, the slope corresponds to the −1.8 uncontroversial slope. For the impacts between 1 km and 100 m, the average slope is −3.31 while the slope of Hartmann's latest isochrons is −3.4 (Table 1). The average slope for the few distributions ranging below 100 m in diameter is −3.1 while the Hartmann's slope is −2.9.

The conclusion of these measurements is that the crater distributions on landslides are in agreement with Hartmann's isochrons, so that the landslide-time distribution is not explained by a lower or a stepper slope in this part of the curve. The second argument about this issue is that the few distributions on older landslides with impact crater larger than 1 km give exactly the same age with the largest crater as with the smallest ones (Quantin et al., 2004a). We also note that a lower slope would exacerbate the problem of apparent young ages.

The issue of using small craters touches directly on a recent spate of papers criticizing the entire concept of crater-count dating with sub-km-scale craters due to alleged problems of "contamination" by secondary impact craters. This is not simple to discuss because many of the papers have stated that our crater system depends on the assumption that all small craters are primaries, which it does not. McEwen et al. (2005), for example, interpreted Hartmann's isochrons as estimates of the number of primary craters, excluding secondaries, and the first two sentences of Bierhaus et al. (2005) state "Estimates of the relative and absolute ages of geological units on [planetary surfaces] have been based on this assumption," i.e., the assumption that "impact crater populations on solid-surfaced planet and smaller bodies [reflect] direct ('primary') impacts." However, Hartmann has stated that the lunar crater counts are not limited to "primary impacts" but include counts of the whole population outside of obvious secondaries in rays and clusters (i.e., primaries plus "distant secondaries"). It is this combined population of primaries and distant secondaries that is scaled to Mars using the Mars/Moon impact ratios and scaling parameters. Thus, the major objection raised by McEwen et al. (2005) and Bierhaus et al. (2005) to using small crater counts does not apply to our past or present work. Nonetheless, we emphasize that these authors make valuable contributions in discussing what might be called "second-order" problems of statistical clustering and effects of large numbers of distant secondaries. We agree that there are many problems when one is restricted to using small craters: issues of secondary clustering, preferential rapid obliteration of small features, etc. The problem of statistical clustering of secondaries, shown by Bierhaus et al. (2005) to occur on Europa, does not appear to be a major problem in our work. Quantin et al. (2004a) clearly showed individual landslides with low crater densities, superimposed on immediately surrounding regions of high crater densities, as well as landslides with high crater densities in the same Valles Marineris complex. Thus, the range of crater densities and distribution of ages found on landslides is unlikely to be explained by effects of local clustering.

3.5. Could the trend be due to declining cratering rate?

The absolute ages on Mars are statistically confident within a factor of 2 to 4 (Hartmann and Neukum, 2001; Hartmann, 2005). Increasing or decreasing the ages attributed to the landslides shifts the curve in time but does not change the exponential shape of the time-dependence. Assuming the ages determined for landslides are not contaminated by the above effects, the remaining explanation of the increasing in landslide production with decreasing age is that the cratering rate has been regularly decreasing over the last 3 Gyr. We will develop this idea in the next section and test it on landslides and other geologic processes.

4. Test of the decrease of the impact flux over the last 3 Gyr

4.1. Inversion of landslide distribution in term of impact flux

To test the idea that the landslide time-dependence reflects a cratering rate that has been decreasing over the last 3 Gyr, we assume a case of a constant landslide activity over that time period. This is a minimum case because the triggering mechanisms are more probably decreasing with time (see discussion in Section 3.1). Assuming a constant rate of landslide production over the last 3 Gyr, we compute the decrease of the impact flux necessary to produce this constant landslide formation rate. We constrained the computation by using the crater density at 3.5 Gyr. Indeed, the ages related to the crater densities of the lunar and martian surfaces can be assumed robust before −3.5 Gyr taking into account the quality of the lunar chronology calibration before 3.5 Gyr (see review by Neukum et al., 2001).

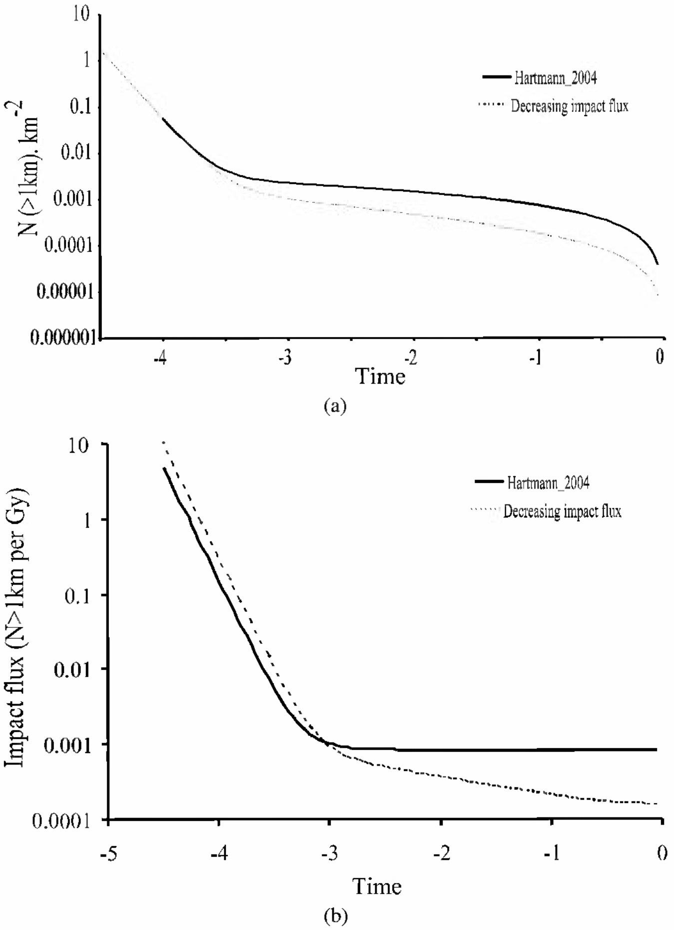


Fig. 3. Model of the decrease of the cratering rate: (a) solid line is the crater density for diameter larger than 1 km vs time corresponding to the isochrons of Hartmann's latest iteration (Hartmann, 2005). The dashed line shows the crater density vs time results from our model of a decreasing crater rate over the last 3 Gyr. We constrained the computation of the model of a decreasing cratering rate by the crater density at 3.5 Gyr assuming that the martian chronology is robust before −3.5 Gyr. (b) Derivation of the cratering rate from the curve plotted in (a). The Hartmann and Neukum age model implies a constant cratering rate over the last 3 Gyr. The model presented here implies a declining cratering rate over this same period by a factor 3.

4.2. Model of cratering rate decreasing over the last 3 Gyr

The inversion shows a decrease by a factor of 3 of the impact flux after 3 Gyr (Fig. 3). That is the decrease of the impact flux necessary to create a constant rate of landslides with time. As

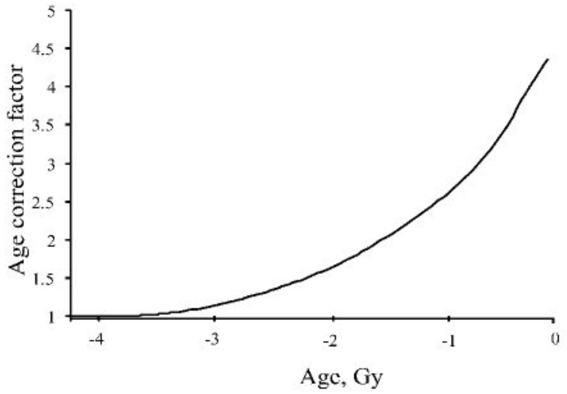


Fig. 4. Consequence of the model of a decreasing cratering rate on the absolute ages: the graph plots the correction factor as a function of the age. The changes in the absolute ages concern only ages younger than 3 Gyr.

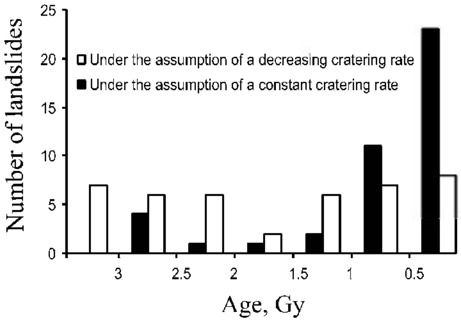


Fig. 5. Application of the age model under the assumption of a constant cratering rate on landslide and comparison with Hartmann and Neukum (2001) model. The number of landslides as function of time is more equally distributed with the model of a decreasing cratering rate than with the constant assumption where landslides increase with time.

we constrained our model by the crater density at 3.5 Gyr, the decrease by a factor of 3 of the crater rate leads to a current cratering rate 3 times lower than the rate usually estimated for the Mars (see comparison with Neukum curve in Fig. 3).

4.3. Implications for age model and applications to landslides occurrence and others re-surfacing processes

Such modification in the absolute cratering chronology would have an effect to increase the ages younger than 50 Myr by a factor of 4, the age around 1 Gyr by a factor of 2.5, the ages around 2 Gyr by a factor of 1.5 and to keep the rest of ages older than 3 Gyr (Fig. 4).

Applying the new age model to the landslides, we have the histogram representation of the ages shown in Fig. 5, indicating that the landslides are more nearly constantly distributed through time than in our earlier result—matching our assumption of the derivation of the new age model.

We can expand this result to more general geological considerations. In the paper of Hartmann and Neukum (2001), the temporal rates of resurfacing were plotted using the martian stratigraphic epochs (Noachian, Hesperian, Amazonian) (Tanaka, 1986; Tanaka et al., 1987, 1992). The results showed that the rate of each type of resurfacing process (volcanism, fluvial and periglacial activity, and impact cratering) declined in the first third of martian history, as expected from other work, but then appeared to increase in the last third. Fig. 6 represents these data using the ages from the latest of Hartmann's chronology (Hartmann, 2005). Hartmann and Neukum (2001) interpreted this unexpected behavior as possibly an effect simply of greater ease of detection of the most recently resurfaced units in Tanaka's studies. The problem is similar to what Quantin et al. (2004a) found among the more clearly interpreted martian landslides.

We applied our new age model to the resurfacing rate from Tanaka taking into account the decrease of the cratering rate over the last 3 Gyr. We found that, except for fluvial processes, all the geologic processes are constant or declining over the last 3 Gyr (Fig. 6). Also for combination of the geologic resurfacing, the trend is approximately constant over the last 3 Gyr in contrast to Hartmann's model for which the resurfacing processes apparently increased in recent time (Fig. 6e).

5. Discussion

5.1. Relevance of a declining cratering rate to the other records in the inner Solar System

We regard the assumption of a constant cratering rate to have been a reasonable working assumption for the first generation of models (i.e., Hartmann and Neukum, 2001; Bottke et al., 2005a). The literature on this subject has been equivocal (Table 2), with some workers assuming a constant rate since ∼3 Gyr ago (Hartmann, 1965, 1966b, 1970; Neukum and Ivanov, 1994; Neukum et al., 2001), some workers suggesting a secular decline by a factor ∼3 (i.e., Ryder et al., 1991; Durda et al., 1998; Marzari et al., 1995), some suggesting an increase over the last 500 Myr (McEwen et al., 1997), and some also emphasizing possible saw-tooth spikes due to asteroid break-up events and 20 Myr-half-life sweepup of debris (Hartmann, 1970; Marzari et al., 1995; Zappala et al., 1998; Nesvorny et al., 2002). The terrestrial impact record is strongly biased by the resurfacing processes on Earth, but the record over the last 100 Myr gives an idea of the of the true impact rate (Grieve and Shoemaker, 1994). The lunar impact history is very well constrained for the period between 3.8 and 3.2 Gyr by many of the samples obtained by American Apollo and soviet Luna missions. However, the last 3 Gyr are only constrained by a few ages less than 1 Gyr obtained from material from young events such as the ejecta from the Copernicus impact (Neukum and Ivanov, 1994; Neukum et al., 2001). However, others authors have suggested that the cratering rate has been decreasing by a factor of 2–3 over the last 3 Gyr based on analysis of the Apollo lunar samples (Ryder et al., 1991; Culler et al., 2000; Hartmann et al., companion paper). The impact flux over this period is assumed to be dominated by the asteroids (Neukum and Ivanov, 1994; Neukum et al., 2001; Werner et al., 2002; Bottke et al., 2005a). Evolutionary models of the asteroid belt also predict a decrease of the impact flux in the inner Solar System by a factor of 3 over the last 3 Gyr (Durda et al., 1998; Davis et al., 2002). The decrease in impact flux by a factor

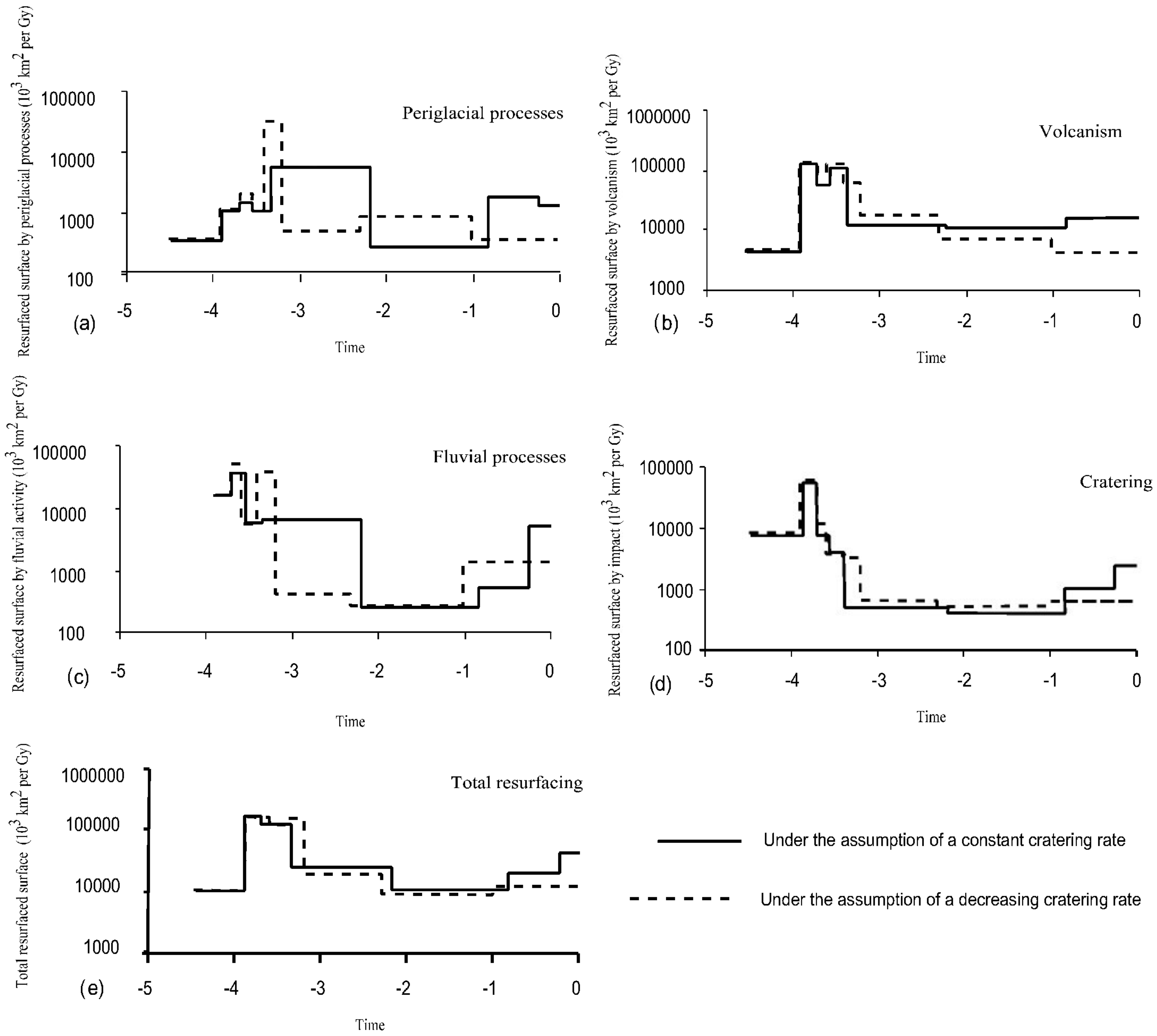


Fig. 6. Application of the age model under the assumption of a constant cratering rate on resurfacing processes and comparison with Hartmann and Neukum (2001) model. For all the processes, we plotted their time-dependence using the epochs defined by Tanaka (Tanaka, 1986; Tanaka et al., 1987, 1992), following the method of Hartmann and Neukum (2001). Two distributions are shown. The solid line uses the latest iteration of the crater chronology (Hartmann, 2005), which assumes constant cratering rate over the last 3 Gyr, but the dashed line shows the data according to our new age model with declining cratering over the last 3 Gyr. Ages before 3 Gyr are essentially the same in the two models. (a) Periglacial processes, (b) volcanic resurfacing, (c) fluvial processes, (d) impact cratering, (e) resurfacing from all kind of processes.

of 3, as suggested in the current analysis, is enough to produce a uniform rate of landslide production and either a decline in or a constant rate of the resurfacing over the entire planet. This hypothesis to explain the time-distribution of landslide and of resurfacing processes is consistent with dynamical models and some lunar absolute ages.

5.2. Current cratering rate

Our inversion test not only proposes a decreasing cratering rate since ~3 Gyr ago, but also a final present day rate about 1/3 as great as the previously used values, in order to increase the inferred ages of the most recent landslides. This is not implausible for Mars. Furthermore, it falls within Hartmann's estimated isochron uncertainty of a factor of 2 to 4.

The martian rates we have used are derived from the Moon, and so, in principle, a reduction in the present day martian rate has the effect of reducing the inferred present day lunar rate. The present day lunar rate is virtually unknown from lunar data. The best data for the current rate thus comes from Earth itself (and must be converted to the Moon and Mars though parameter-dependent scaling assumptions leading to

Table 2
Different assumptions for the cratering rate over the last 3 Gyr in the inner Solar System

Hypotheses about the impact flux over the last 3 Gyr in the inner Solar System	References
Constant	Hartmann (1965, 1966b, 1970), Neukum and Ivanov (1994), Neukum et al. (2001), Grieve and Shoemaker (1994) (over the last 100 Myr)
Decreasing	Ryder et al. (1991), Durda et al. (1998), Davis et al. (2002), Marzari et al. (1995), Culler et al. (2000)
Increasing (over the last 500 Myr)	Neukum et al. (1975), McEwen et al. (1997), Culler et al. (2000)
Spikes due to asteroid break-up events	Hartmann (1970), Marzari et al. (1995), Zappala et al. (1998), Nesvorny et al. (2002)

many uncertainties). In early studies on tabulating craters in various Canadian geologic units, Hartmann (1965) derived a production rate expressed in terms of craters of $D > 1$ km: 1 to 15×10^{-4} craters/km^2 Gyr. Using the right scaling relationships to have a production rate for craters of $D > 20$ km, the results implied a terrestrial production rate for craters of $D > 20$ km of 0.45 to 6.8×10^{-15} craters/km^2 yr (Hartmann, 1965). Neukum (1983) independently studied the lunar crater production rate and developed an equation for its time dependence (see also Neukum et al., 2001; Neukum and Ivanov, 1994, Eq. (18), p. 389). It gives a current lunar production rate (craters of $D > 1$ km/km^2 per yr $= 8.38 \times 10^{-13}$). Applying the right diameter correction, this gives 3.81×10^{-15} craters/km^2 yr for craters of $D > 20$ km. Neukum and Ivanov's (1994) work on lunar data give an approximate Neukum-derived estimate for the terrestrial production rate of craters of $D > 20$ km of $5.5 \pm {\sim}2 \times 10^{-15}$ craters/km^2 yr.

Reviewing the previous works on this subject, we have the following estimates of production rates on Earth for craters of $D > 20$ km:

- $6.3 \pm 3.2 \times 10^{-15}$ craters/km^2 yr (Shoemaker, 1977),
- $3.5 \pm 1.3 \times 10^{-15}$ craters/km^2 yr (Grieve and Dence, 1979),
- $5.5 \pm 2.7 \times 10^{-15}$ craters/km^2 yr (Grieve, 1984),
- $4.5 \pm 2.0 \times 10^{-15}$ craters/km^2 yr (Shoemaker and Shoemaker, 1990),
- $5.6 \pm 2.8 \times 10^{-15}$ craters/km^2 yr (Grieve and Shoemaker, 1994).

From this review of the literature, we take note that the estimated current impact rate ranges over more than 50% and the lower end of the quoted error bars extends to about half the estimated value. Based on the uncertainties upon which the current impact rate on Mars is based, we conclude that it is not implausible to suggest that the cratering rate for craters in the size range above a few hundred meters is 1/3 the average rate that applied over the last 3 Gyr.

5.3. Record of the cratering rate history over the last 3 Gyr on Mars

Martian landslides have been actively occurring over the last 3 Gyr (Quantin et al., 2004a) and therefore have recorded the cratering rate over this period. The apparent increase in rate of landslide formation within Valles Marineris is difficult to explain and, as we have shown, the best hypothesis is that the impact flux has declined over the time period recorded by the landslides. One of the implications of the present work is the relevance of the declining impact flux to surface age dating not only of Mars but also the entire inner Solar System.

5.4. Consequences for the martian chronology

A declining cratering rate leads to an increase in the absolute ages by a factor dependent on the age of the surface. This means that the widely cited ages based on models assuming a constant cratering rate (i.e., Hartmann and Neukum, 2001) need to be adjusted. A decreasing cratering rate in the age model leads to an increase in the absolute ages by a factor that depends on the age surface. The younger the age derived under the old systems, the greater the necessary correction. Nonetheless, the consequent age corrections are essentially at the level of the factor 2–4 uncertainty cited by Hartmann and Neukum (2001) and Hartmann (2005). Combining these effects, the possibility of declining flux and the uncertain effective mean impact velocities for the smallest craters (which may be dominated by secondaries), we reinforce the fairly large uncertainties that have been discussed for the isochron system (Hartmann and Neukum, 2001; Hartmann, 2005), namely factors of 2 to 4. All the sources of error including the assumption of a constant cratering rate lead to having a larger error bar than usually assumed using small impact craters to date typically young and small surfaces.

These consequences of our new age model are especially relevant to recent geological activity and evidences of recent climate changes. Many landforms are lightly cratered, such as gullies (i.e., Malin and Edgett, 2000), polar layers (i.e., Herkenhoff and Plaut, 2000), and putative glacial features (i.e., Mangold, 2003; Neukum et al., 2004). These young surfaces could be older by a factor 4, which raises the question of the timescale of possible climate changes. Applying our new age model to previous cited age of ∼1 Myr for these features, we derive an age of ∼4 Myr which still implies a very recent period of martian history.

6. Conclusion

Landslide activity and resurfacing processes on Mars show an apparent increase over the last 3 Gyr when one assumes a constant cratering rate. These data instead support a decline in inner Solar System cratering rates by about a factor 3 since 3 Gyr ago, not unlike predictions based on asteroid belt collision models and data from lunar samples and not unlike the errors in the current impact rate estimations. Such a model would imply that the youngest ages derived under the former assumptions of a constant cratering rate should be increased. Under such a model, the rate of landslides and other forms of geological activity in the last 3 Gyr are found to be more constant than under the earlier models, a conclusion which we suggest is more plausible than increasing geological rates of activity.

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