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Surface formation rates and impact crater densities on Venus

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Abstract. Impact crater density has been used to estimate relative ages of major Venus geologic units, typically based on the assumption of short, globally synchronous formation periods. The total number density of craters is the only parameter which may be quantified for most Venus subregions, in contrast to the size-frequency analysis often used for other planetary studies. This paper examines the statistical limits on such crater counts and the predicted crater density for various possible time-varying surface formation rate functions. These results show that (1) the true mean crater density is poorly constrained due to the limited sample size provided by aggregate geologic units, and (2) any given crater density can be accommodated by a very short pulse of unit formation at some age T, Gaussian-distributed formation functions of mean age $<T$, exponential functions with initiation ages between T and $2T$, or a host of other more complicated rate functions. These results, when coupled with the unknown rate of crater removal by tectonic or volcanic activity, indicate that the crater counts for specific landforms on Venus offer little constraint on the relative timing or duration of their development. The hypothesis of globally synchronous formation of landforms such as volcanoes or coronae cannot be validated with the available crater data.

1. Introduction

Establishing a relative age progression for surface units is an important goal in planetary geology and geophysics. Impact crater populations have long been a principal method for estimating relative planetary surface ages, and these dates have been linked to an absolute chronology based on the lunar cratering record and sample ages. Initial studies of the Venus crater population, however, revealed some properties which hamper statistical age dating efforts. First, the thick atmosphere acts as an effective barrier to bolides, inhibiting the production of craters smaller than ~5 km in diameter and considerably lowering the overall population of craters <35 km [*Phillips et al.*, 1992; *Schaber et al.*, 1992; *McKinnon et al.*, 1997]. The low total number of craters on Venus and the absence of any record for small impactors dictates that only the integrated areal density for craters of all sizes may be used for age estimation. The size-frequency distribution of craters, which is commonly used to establish surface ages for other bodies, may only be studied for regions which are nearly global in scale.

Second, the global distribution of impact craters is potentially indistinguishable from a spatially random collection, such that simple clustering analysis will not yield strong constraints on the age of surface units. The spatially random (or nearly so) distribution and relative paucity of embayed and tectonically deformed craters has been cited as evidence for a global resurfacing period between 300 and 750 m.y. ago, during which the crater record of Venus was completely reset [e.g., *McKinnon et al.*, 1997]. The rate of plains resurfacing is in debate, with some authors favoring short pulses of catastrophic magma output [e.g., *Schaber et al.*, 1992; *Basilevsky and Head*, 1998] and others suggesting more punctuated events over a longer period of time [e.g., *Phillips et al.*, 1992; *Phillips and Hansen*, 1998]. Recent work by *Hauck et al.* [1998] questions whether the plains represent a discrete time marker in Venus history and demonstrates that more distributed ages for the plains cannot be rejected on statistical grounds.

Another major point of contention rests on whether local stratigraphic progressions correspond to globally synchronous events or simply to common variations in the volcanic and tectonic behavior of different areas at different times [e.g., *Hansen and Willis*, 1996; *Basilevsky and Head*, 1998; *Guest and Stofan*, 1999]. In the absence of surface age dates, the answer to this issue is sought in the cratering record and the stratigraphy revealed by geologic mapping of Magellan image data [e.g., *Gilmore et al.*, 1997; *Price et al.*, 1996; *Price and Suppe*, 1995; *Namiki and Solomon*, 1994]. Several authors have proposed that the populations of craters on grouped occurrences of specific terrain types from across the planet have differences which correlate with the inferred stratigraphy and that these populations further support the notion of globally synchronous geologic events (e.g., tessera, corona, and edifice formation). This paper examines the basic problem of characterizing populations of this type, the limits on their interpretation in terms of surface formation rate, and the conclusions of previous studies regarding the geologic history of Venus.

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2. Statistics of Aggregate Crater Counts

In a survey of major Venus landforms, *Price et al.* [1996] estimate surface ages by combining the total area and crater population of widely dispersed regions to arrive at an areal density ρ. They next assume that the observed crater density for an aggregate region is "the most probable density" and define a distribution of possible mean surface ages about this value based on 2σ error bars consistent with samples of a binomial distribution (their Figure 10). The various occurrences of a given terrain type are assumed to form in a short period of time, such that the uncertainty in crater density translates only into a range of possible central age values. This assumption of synchronous formation for similar landforms stems from stratigraphic analysis of Magellan image data [e.g., *Basilevsky and Head*, 1995]. A similar approach to crater age dating has been taken by other authors. This methodology, however, has a significant flaw in that the inherent assumptions cannot be tested with the available data.

While it may be reasonably argued that the lower crater abundances found for volcanoes, coronae, and other features are statistically unlikely to be outliers of the global crater population, this result does not lead directly to the inference of globally synchronous formation for each of the subregions. The constraints placed on plains formation by the abundance of flooded or deformed craters (which remain a topic of debate) do not extrapolate to aggregate areas which comprise only 2-8% of the venusian surface. Any difference in crater counts and flooded/deformed crater abundance may arise due to a wide range of differing surface production and resurfacing events. The case for synchroneity must be justified for each type of landform, and as shown below this becomes a challenge when the available crater populations are small.

The first problem with using Venus craters as a dating tool lies in the uncertain value of the areal density. To illustrate, assume that the craters on a suite of patches across Venus sample an idealized global population formed over some arbitrary time period. It does not matter, for this example, whether the terrain formed synchronously or was widely dispersed in time; all we are concerned with is the final average crater density. The probability $P(N)$ of obtaining a count of N craters for a certain total area is given by the binomial distribution. For some reasonable large number of craters, this may be approximated by a Poisson distribution about a mean m with standard deviation given by $m^{0.5}$:

$$P(N) = \frac{e^{-m}\, m^N}{N!} \tag{1}$$

Because the number density of craters on Venus is small, we can in most cases obtain only one significant sample of this distribution of possible N values for a chosen landform. We therefore have very little constraint on the relationship between this single measurement and the true mean. "True mean" refers here to the average value one would obtain if, for example, a thousand planets with the same subregions were cratered at the same rate. The crater-count values from each planet would then be distributed about the mean as predicted by (1). Given that we have only one Venus, our estimate of m is limited to one sample from this population. The true value for m could be further constrained by subdividing the sample region into statistically significant areas and examining the distribution of N, but the paucity of craters makes this impractical. The probability distribution of crater densities inferred by assuming that m=N thus cannot be verified.

This problem does not arise in many other planetary crater-counting studies because m is typically much higher for the area of interest. As such, the percentage error incurred by assuming that the observed density equals the true mean is relatively minor. *Plaut and Arvidson* [1988] suggested a minimum sampling area criterion to avoid large potential error bounds on the measured crater count. For Venus, however, values of N as low as 8-10 anchor the low (i.e., young) end of a relative age spectrum, so we must be cautious. An example for m=15 is shown in Figure 1. A measured population of craters may lie anywhere within the range defined by the Poisson distribution (the solid line in Figure 1), though it is statistically more likely to be near the central region. *Price et al.* [1996] assume that the mean crater abundance (and by assumption the mean age) lies within $\pm 2N^{0.5}$ of the observed count, with a normal probability density function. If, however, the true mean of the distribution lies to one side or the other of the observed value, then the probability of obtaining counts in the opposite direction is much less than that inferred. We could, for example, plausibly count only 10 craters on a single sampling. On the basis of *Price et al.*'s [1996] methodology, this is the central value of the distribution labeled N_{obs} in Figure 1. In this case, however, the true mean (15 craters) lies 1.6 standard deviations away from our assumed mean (10 craters), and one could infer that a value of N=5 is just as likely as the actual central value (m=15) of the distribution.

The "error bars" inferred from any one crater count may thus encompass m, but it is erroneous to imply that values even two standard deviations distant from the measured density are less likely to be the correct mean. The only way to improve this situation would be to subdivide the sample area and examine the distribution of N among the subareas, but the low density of craters precludes this approach. We conclude that little constraint may be placed on the statistical likelihood of possible density values to either side of a single sample and that such a distribution may potentially be highly skewed if the sample happens to fall far from the true mean. These results do not invalidate the observation that volcanoes, coronae, and some other landforms have lower crater densities than the plains [*Price et al.*, 1996], but they do show that the estimated

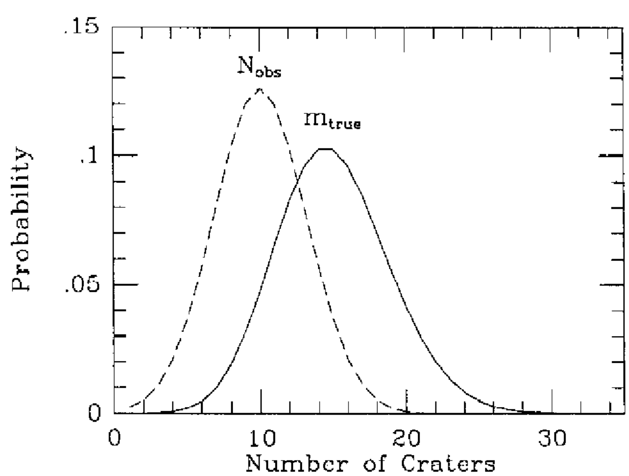

Figure 1. Example of possible Venus crater count errors. The true Poisson distribution of possible values for N, with a mean m of 15, is given by the solid line. The dotted line shows the Gaussian probability distribution inferred by the methods of *Price et al.* [1996] based on a single count of N=10. Note that the actual mean of the population, m, is considered to be of lower probability based on this methodology than a value of N=m/2.

errors should be taken only to encompass the mean value rather than to constrain its probability distribution.

3. Formation of Craters on a Terrain

Assuming that one accepts a crater count as a plausible representation of the mean abundance on some landform, what can be inferred from the value of N? The notion of a "mean surface age" has been invoked under the assumption of synchronous terrain formation, but the crater density is not uniquely fit by any one formation rate model. To properly constrain Venus crater age dating, we must analyze possible distributions of geologic unit emplacement rate over time, and we cannot constrain a priori whether grouped occurrences formed over any particular distribution.

To begin, we assume that at some time t a certain unit is forming at an areal rate $R(t)$, with units of km^2/yr. If there has been no burial of this unit by other materials, then the total presently observed area A_{tot} is given by:

$$A_{tot} = \int_{\infty}^{0} R(t)\,dt \tag{2}$$

where time is taken to run from the present (t=0) backwards to "infinite" age. The actual shape of the $R(t)$ distribution is unknown, but we may postulate any number of simplifying scenarios, including an extremely short duration for unit formation, a uniform rate over some specified time interval, an exponential decrease in production from a chosen start time, or a Gaussian-like rise and fall in rate about some central maximum production age.

Impact craters are assumed to form at a rate which is related to their radius. The total number of craters formed per unit area per unit time is F, and over the likely age range of the Venus surface it is reasonable to expect that this value will be constant. The total number of craters formed per unit time on a particular type of terrain across the planet, assuming that all outcrops are at least large enough to accommodate a crater several tens of kilometers in diameter, at some time t is

$$F\,A(t) = F \int_{\infty}^{t} R(t')\,dt' \tag{3}$$

The total number of observed craters is simply the integral over time since the start of unit formation:

$$N = F \int_{\infty}^{0} \left[\int_{\infty}^{t} R(t')\,dt' \right] dt \tag{4}$$

This shows that the number of craters is critically linked to the form of the rate function for unit formation. To illustrate this relationship, we consider three types of statistical distribution: uniform, Gaussian, and exponential.

A uniform $R(t)$ function implies that the process which forms a certain unit operates at a constant rate over some interval of time. The description of such a process requires a mean age t_m and duration 2σ:

$$R(t) = \frac{A_{tot}}{2\sigma} \qquad t_m + \sigma \geq t \geq t_m - \sigma \tag{5}$$

The resulting areal crater density ρ is

$$\rho = \frac{N}{A_{tot}} = F\,t_m \tag{6}$$

This shows the expected result that a uniform distribution of surface ages will have a crater count proportional to the mean age of the total area. The observed crater density constrains the span of time over which the terrain-forming process may have been active to the extent that no surface features may be older than $2t_m$ (i.e., the value of σ is limited only to the range $0<\sigma<t_m$).

A Gaussian rate function implies that the unit of interest formed by a symmetric ramp-up and ramp-down of the required process (volcanism, tectonism), centered on some mean time t_m with standard deviation σ. The normalized rate function is

$$R(t) = \frac{2\,A_{tot}}{\sqrt{2\pi}\,\sigma\,\mathrm{erfc}\left(\frac{-t_m}{\sqrt{2}\sigma}\right)} \exp\left[-(t-t_m)^2/2\sigma^2\right] \tag{7}$$

where erfc denotes the error-function complement. This equation has been scaled such that the observed terrain area forms within the time period from infinite age to the present. Using this form, (4) yields

$$\rho = \frac{N}{A_{tot}} = F\left[t_m + \frac{\sqrt{2}\sigma \exp(-t_m^2/2\sigma^2)}{\sqrt{\pi}\,\mathrm{erfc}(-t_m/\sqrt{2}\sigma)} \right] \tag{8}$$

Figure 2 illustrates the normalized crater density obtained for various normalized mean ages and standard deviations using the Gaussian function. Globally synchronous formation is modeled by very low values of σ. There is little difference in crater density among units whose mean age is greater than the standard deviation of the particular $R(t)$ function. Once $t_m>\sigma$, the functional relationship is indistinguishable from the behavior of a uniform function of indeterminate duration. The crater density for a surface again offers little constraint on the duration of activity.

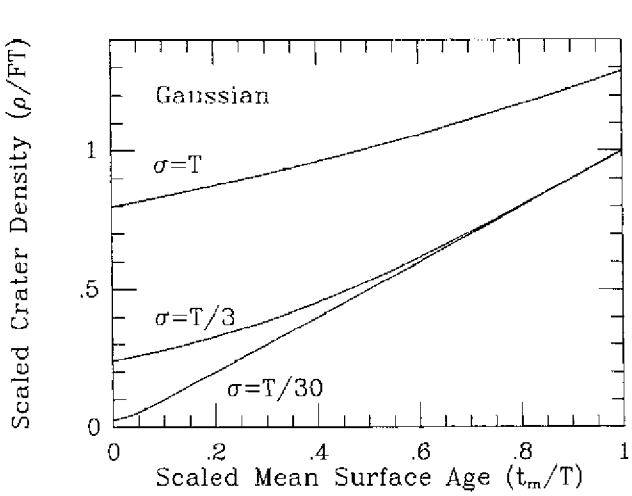

Figure 2. Crater density as a function of mean surface age and the standard deviation of formation rate for a Gaussian formation function. Note that the duration of surface formation is poorly defined by a simple crater density. All values are referenced to some arbitrary time T and impact flux F.

An exponential distribution function implies that the terrain formed by an initial rapid pulse followed by a longer ramping down of activity. The average value of an exponential function does not have the same interpretation as for a Gaussian function, and the mean age of the surface must be replaced by an "initiation age" t_o:

$$R(t) = \frac{A_{tot}}{\sigma(1-\exp[-t_o/\sigma])}\exp\left[-(t_o - t)/\sigma\right] \qquad t < t_o \tag{9}$$

The crater density on such a surface is given by

$$\rho = \frac{N}{A_{tot}} = F\left[\frac{t_o}{(1-\exp[-t_o/\sigma])} - \sigma\right] \tag{10}$$

and results for various values of t_o and σ are shown in Figure 3. These results show that crater densities on older surfaces are most sensitive to changes in the standard deviation of the rate function. As above, any single crater density cannot uniquely constrain both the initiation age and duration of terrain-forming processes.

Figure 4 presents a set of numerical solutions for the standard deviation σ of $R(t)$ as a function of t_m (Gaussian) and t_o (exponential). For a chosen value of ρ, the mean age for a Gaussian function has a maximum value where σ~0, consistent with a very narrow pulse of activity. Note that the same point also describes the initiation age of a very narrow exponential pulse. For the exponential form, the maximum initiation age is twice the value found for σ=0, and the resulting form of $R(t)$ is equivalent to the slowest possible uniform case. Any given crater density thus may be accommodated by (1) geologic activity of very short duration centered on $T=N/(FA_{tot})$, (2) Gaussian formation functions with mean values younger than T, (3) exponential formation rates with initiation ages between T and $2T$, or (4) uniform rates with maximum initiation ages of $2T$.

For example, *Price et al.* [1996] estimate that large volcanoes have ρ=0.51±0.32 craters per 10^6 km^2 and suggest a mean surface age of 72±45 m.y. Using their implied cratering rate and error bounds, this range of densities may also correspond to a slow uniform formation rate beginning at <234 m.y, to a brief spike of activity anywhere between 27 and 117 m.y, or to a currently escalating Gaussian rate function. Some possible scenarios for just the central estimate of ρ=0.51 are illustrated in Figure 5, and it is clear that little constraint may be placed on the relative timing (i.e., the synchroncity) of large volcanoes across Venus. Obviously, one could also develop more complicated rate functions to match the same data, and we conclude that any interpretations of crater density are nonunique and poorly constrain both the average age and relative timing of subregions of a particular landform.

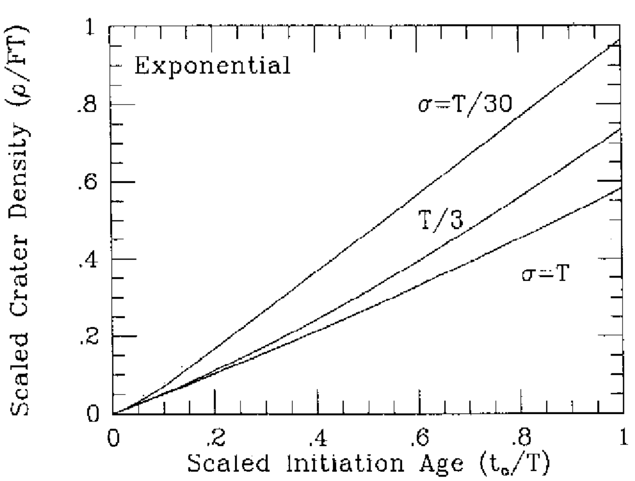

Figure 3. Crater density as a function of surface initiation age and the standard deviation of formation rate for an exponential formation function. All values are referenced to some arbitrary time T and impact flux F.

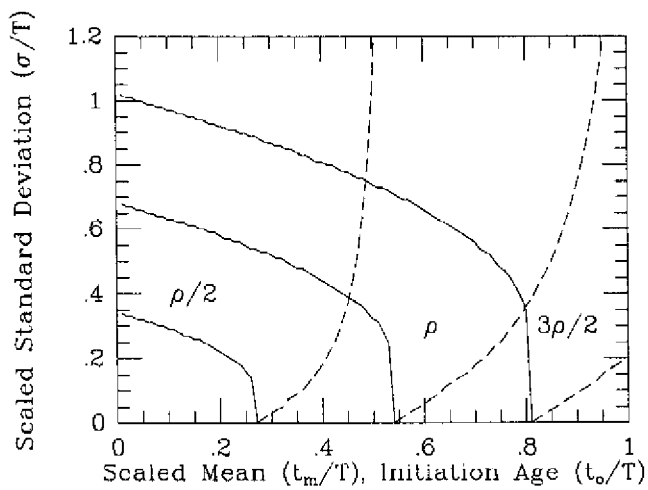

Figure 4. Standard deviation of formation rate versus mean surface age or initiation age for Gaussian (solid lines) and exponential (dashed lines) functions. Curves for three possible crater densities are shown. All values are referenced to some arbitrary time T and impact flux F. Note that very wide exponential distributions correspond to low uniform rates of emplacement.

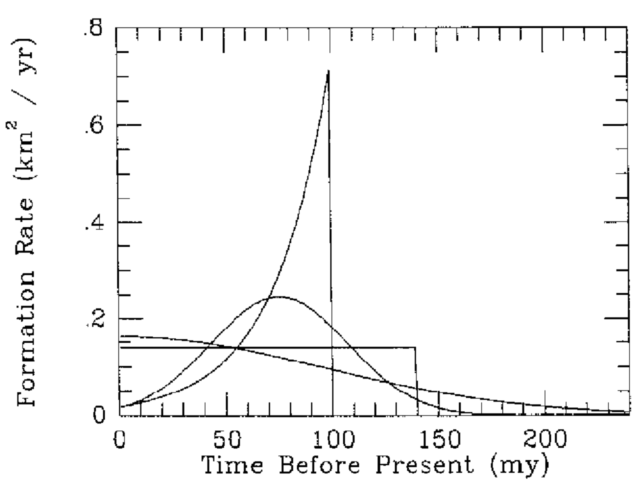

Figure 5. Formation rate curves for large volcanoes on Venus. These four curves represent identical present-day crater densities for large volcanoes mapped by *Price et al.* [1996]. Total terrain area is 19.52 x 10^6 km^2, and the average cratering rate is assumed to be 0.0066 (10^6 yr 10^6 km^2)$^{-1}$, consistent with their assumed 300 m.y. age for the plains. These curves represent only the observed crater density for this surface; densities within the possible error bars of the crater count would considerably widen the range of plausible functions.

4. Discussion

A final concern in surface age dating deals with the unknown rate of crater removal on various landforms. As recognized by *Price et al.* [1996], the fact that large volcanoes and coronae have fewer craters than the regional plains is consistent with the stratigraphic position of their latest flows, but the detailed history of such constructs cannot be addressed with the available data. The difficulty arises in that different landforms may remove craters (by volcanism, tectonism, or annealing) at very different rates. For example, the plains may be made up of rapidly emplaced flow units which individually cover a small area, but then remain static through to the present time. This "monogenetic" behavior contrasts with the longer emplacement history of a large edifice. While the upper surface appears to be younger due to recent resurfacing, the volcano itself may have begun to form prior to plains emplacement. Crater loss is simply more efficient in regions of repeated resurfacing, and the inference of a younger age for the volcano incorrectly lumps its entire development into a single period of time.

These results show the following: (1) The actual mean crater density on an aggregate area is not well constrained by the limited data, since we in effect have only one sample of a probability distribution. The error bars derived from the Poisson approximation can only be taken to encompass the mean, not to define its probability density function. (2) Any given crater density may be matched by a wide range of possible formation rate functions. Taken together, these two conclusions suggest that Venus crater studies cannot be used to support stratigraphic inferences [e.g., *Basilevsky and Head*, 1998], and some interpretations of these data may oversimplify complex and time-varying geologic events. The hypothesis of globally synchronous formation for landforms which occupy a small fraction of the planetary surface cannot be tested with the available data. Only in situ measurements of surface samples are likely to resolve these issues.

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