VENUS RESURFACING RATES: CONSTRAINTS PROVIDED BY 3-D MONTE CARLO SIMULATIONS

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Abstract. The range of surface ages on Venus and the rate of recent volcanism are two major questions that can be addressed through an analysis of Magellan images. We report on a 3-D Monte Carlo resurfacing model that seeks to explain the resurfacing history of Venus by simulating the evolving surface under the competing processes of impact cratering and volcanism. By incorporating the observed size distribution of volcanic forms on Venus, and the assumptions of constant volcanic and impactor fluxes, we seek a solution that is consistent with the observed impact crater population. In the Monte Carlo simulations, a volcanic flux of 0.37 km^3/yr, operating for 550 m.y. on initially craterless surfaces, yields surfaces that are statistically similar to Venus'. It is shown that the statistics of the impact cratering record are inconsistent with an equilibrium resurfacing model.

Introduction

The average crater density on Venus, as revealed by detailed radar images from the Magellan spacecraft, implies that the surface of the planet is approximately 500 million years old [Schaber *et al.,* 1992]. The nature and rates of the planetary resurfacing processes are recorded in the styles and distribution of modified craters. Only a small number of craters are apparently modified by volcanism [Phillips *et al.,* 1991]. Schaber *et al.* [1992] report that out of a total of 912 identified impact craters, only 4-7% are partially embayed by volcanic lavas, while 33% are tectonically modified. Any process that was removing craters gradually such as chemical or physical weathering, aeolian erosion or burial, viscous relaxation or volcanic flooding would be expected to leave a suite of craters in various states of degradation. Two hypotheses have recently been put forth to explain this conundrum. Each involves a unique combination of resurfacing spatial scales and time dependence.

The first hypothesis, the single production age or 'catastrophic resurfacing' model, is that resurfacing rates on Venus were sufficiently high to effectively destroy all craters in the past, and then rapidly declined, allowing subsequent crater preservation in pristine form [Schaber *et al.*, 1992; Head *et al.*, 1992; Phillips *et al.,* 1992]. The age of this change in surface activity may be approximately constrained by crater densities, and the subsequent resurfacing rate may be quantified by the small but nonzero number of partially embayed craters.

The second hypothesis is that there has been a relatively constant rate of 'regional resurfacing' [Phillips *et al.,* 1991; Head *et al.*, 1992]. Statistical analyses of the spatial distribution of observed craters reveals that they are consistent with complete spatial randomness, ruling out extensive resurfacing events over large areas in the last 5 - 10 x 10^8 years. This hypothesis suggests that the characteristic scale of the resurfacing events which dominates the steady-state evolution of the surface is smaller than the scale of randomness of the craters. The absence of any small craters due to the thick atmosphere means that this scale of randomness is large enough to allow a significant, perhaps the dominant, portion of the volcanic resurfacing activity to occur on a scale that is less than the average inter-crater separation. The regional resurfacing model [Phillips *et al.*, 1992] was developed by considering a characteristic regional patch size of fractional area a, and a characteristic resurfacing rate, ω. They found that impact crater spatial randomness was preserved, and crater densities accounted for, with patch sizes less than 0.0003 (140,000 km^2), and frequencies greater than once per 150,000 years. Additionally, the statistics of the observed crater population could be accounted for by considering patch sizes greater than 0.1 (4.6 x 10^7 km^2), and frequencies of less than once per 50 million years. These two solution branches were considered in their model to represent a steady state between impact cratering and resurfacing events.

These two simple resurfacing schemes describe the opposing ends of a continuum of possible resurfacing histories. They are constrained by the observed crater population in a number of ways. First, there is the important observation by Phillips *et al.* [1992] that the observed impact crater population cannot be distinguished from a spatially random one. For the purpose of determining an average volcanic resurfacing rate, the limitations of the cratering statistics forces us to use the apparent randomness of the distribution of impact craters as a constraint in modeling efforts, and to be content at present with predicting only globally averaged rates. The second important observation is the small number of observed partially embayed craters. Any quantitative model of resurfacing processes must correctly account for this, and it can provide an important constraint on both spatial and temporal scales of resurfacing.

Two dimensional models that consider patches of planetary surface that are reworked by impact cratering and volcanic resurfacing can only be constrained by the areal and size frequency distributions of the observed crater population. For this reason, they are unable to distinguish between the two end member models discussed above. Furthermore, recently Herrick [1993] has discussed the importance of the non uniformity of the distribution of craters with elevation. In order to choose between the widely differing predictions of Venus' surface age, a more complete picture of the way impact craters are removed and modified on Venus must be incorporated into a resurfacing model. We have implemented a 3 dimensional Monte Carlo resurfacing model, simulating the evolving surface of Venus under the influence of an impactor flux, and a variety of styles of volcanic resurfacing [Bullock *et al.,* 1992]. Simulated surfaces with a wide range of constant volcanic resurfacing rates have been generated. The evolution of partially embayed craters is tracked during each run, and the resulting crater populations may be compared with observations. By incorporating constant resurfacing rates and a power law distribution of flow sizes we predict the volcanic fluxes necessary for achieving a steady state between impact crater production and annihilation. Similarly, we show the resurfacing rates that are necessary to produce surfaces that are in crater production with predicted percentages of partially embayed impact craters.

The Monte Carlo Model

The computer simulation of the planetary surface is represented on a 3-D grid, with a surface resolution of 5 km and a vertical resolution of 100 m. The total grid represents an area of 4 x 10^8 km^2, the approximate surface area of Venus. The surface is initially flat, with volcanism and impact cratering being the only forces shaping subsequent topography. Monte Carlo methods are used to randomly place impact craters, at rates and diameters derived from the observed mass distribution of Earth and Venus crossing asteroids and comets [Shoemaker *et al.,* 1991]. The impact crater diameters are chosen from

$$N(D) = C_1 D^{-b}$$

Rim heights are calculated from the diameter/height relationships for lunar impact craters [Pike, 1977].

$$RH = C_2 D^{-c}$$

A wide range of volcanic features are represented on the planet. The observed size-frequency distribution for volcanic features on Venus [Head *et al.*, 1992] is used to randomly select volcanic forms and to place them on the planet. Again, the observed distribution is fit to a power law for the Monte Carlo simulation,

$$N(V) = C_3 V^{-a}$$

The areal extent of shield fields, large volcanoes, and lava floods is determined in the simulations by sampling the appropriate distributions for the feature type from Magellan data [Head *et al.,* 1992]. Lava flow features are modeled using an energy minimization technique to simulate the effects of local topography on the shape and extent of flows. Time steps of approximately 1 million years are chosen; the model selects craters at a given cratering rate and volcanic features at a specified volume rate. Superimposed craters and volcanic features are analyzed by their relative placement and topographies. Volcanic features may completely obscure old impact craters, partially cover old crater floor, or simply flow around the crater rim. The surviving craters are counted and binned at each time step. Special attention is paid to the number of partially embayed craters. Their production is monitored and plotted as a function of time.

The size frequency distribution is calculated at the end of each run, which varies in total duration from 1 to 3 billion years. By varying the ratio of cratering rates to volcanic fluxes, surfaces of different crater populations, and therefore ages, can be produced. Depending upon the distribution of volcanic feature size and rates, surfaces with varying densities of partially modified craters may also be produced.

The severe roll off of the crater size-frequency distribution due to atmospheric filtering is approximated by introducing a low diameter cutoff at a crater diameter of 16 km. Although this ignores the preferential removal of small craters, the cutoff has been selected to compensate for craters less than 16 km by overestimating the number with diameters between 16 and 32 km, such that the total number of craters will be close to that which would be produced by a more sophisticated treatment of the small-end distribution. Another potential source of error in the model is the way in which the 3 dimensional simulation produces partially embayed craters. An accurate representation of the large numbers and volumes of flows on a planetary surface over geologic time is beyond the computational scope of the present model. Although surface topography partly influences the construction of simulated flows in the model, impact craters become embayed when adjacent flows exceed the crater rim height. Schaber *et al.* [1992], in their assessment of the number of partially embayed craters, use the criterion that some part of the rim material be embayed by adjacent flows. Since the present model requires that the crater rim is actually breached, to some extent the number of partially embayed craters is underestimated. Additionally, recent work on the rim height/diameter relation of Venusian impact craters [Schaber *et al.*, 1992; Sharpton, 1992], reveal that crater rim heights on Venus are slightly greater than those on the moon. Our use of lunar rim height/diameter ratios therefore results in a slight underestimate of the number of lava-breached impact craters. Future enhancements to the model will address the question of the embayment of crater ejecta deposits and the observed ‘dark splotches’ as well as incorporating time dependent volcanic fluxes and improved data on impact crater rim height/diameter ratios.

If enough volcanic flow material is present in the vicinity of the impact crater, the crater may become obliterated during a resurfacing event. In this way, craters are removed or modified in the simulations by the action of volcanic flows. Since actual crater removal and modification processes are vastly more complex than this, there are obvious uncertainties in the numerical estimate of partially embayed craters.

Results

Results for several runs are shown in Figures 1 and 2. In these simulations, surfaces were allowed to evolve for a billion years, reflecting the competing processes of constant-rate impact cratering and volcanism. Figure 1 shows the time evolution of surviving impact craters when the resurfacing rate is high enough for equilibrium between production and destruction processes to be evident after less than 1 billion years. The equilibrium number of craters is significantly less than the number of observed craters on Venus, when the

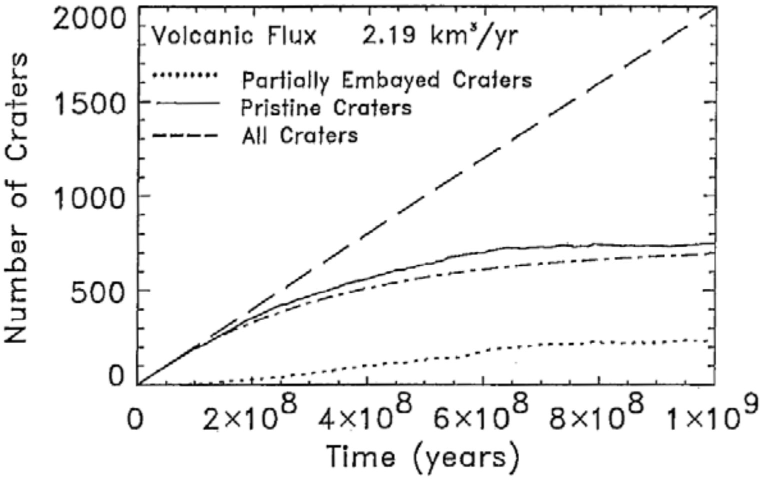

Fig. 1. Model results for a volcanic flux of 2.19 km^3/year. The dashed line represents the production of impact craters without resurfacing. The solid line shows the evolution of surviving craters, and the dotted line shows the evolution of partially embayed craters. A steady state with 750 craters is achieved, with about 30% of them partially embayed. The dot-dashed line shows the result from the analytical model.

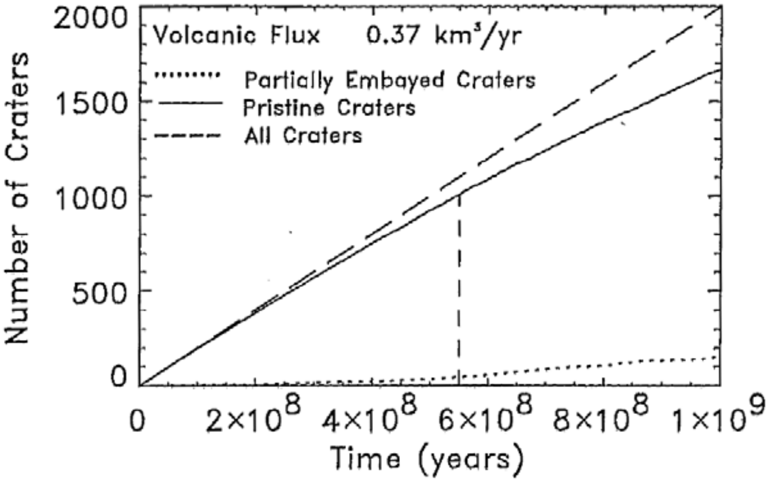

Fig. 2. Monte Carlo model results for a volcanic flux of 0.37 km^3/year. 550 million years is required to obtain approximately 950 craters, with 5% of them partially embayed, as shown by the vertical dashed line.

surface is subjected to a constant volcanic flux of 2.19 km^3/yr. More importantly, as can be seen by the dotted line trace, the fraction of surviving craters that are partially embayed by lava is quite high, at about 30%. By performing simulations with a wide range of resurfacing rates, we have seen that this is a general feature of model runs which have a sufficiently high resurfacing rate to reach an equilibrium number of craters in 1 to 2 billion years. These resurfacing rates always produce a fraction of partially embayed craters substantially greater than that observed. As a check on the numerical algorithms used in the Monte Carlo model, a simple 2-D analytical resurfacing model which predicts only the number of surviving impact craters as a function of time was also developed. The results of the analytical model, for a volcanic flux of 2.19 km^3/yr are also shown in Figure 1.

With the assumptions of a constant resurfacing rate, and an initially crater free surface, the age of the surface and the subsequent resurfacing rate are uniquely determined by the number of observed surviving and partially embayed craters. This result is shown in Figure 2, where a constant flux of 0.37 km^3/yr results in approximately 950 surviving craters after 550 m.y., with 5% being partially embayed by flows.

For the purpose of comparing the results of this 3 dimensional model to those of the 2 dimensional models by Phillips *et al.* [1991], we have performed several runs with parameters that simulate the 2 dimensional parameters of these models. The results of model runs for the two solution branches of the Phillips *et al.* model are shown in Figures 3 and 4. For the ‘small patch’ solution branch, where the resurfacing patch size is 0.0003 or less, with a period of 150,000 years or more, we find that the essential feature of the randomness of the surviving impact craters is preserved (Figure 3). However, for the 3-dimensional runs reported here, a large percentage of the surviving craters (15%) are partially embayed by the lava flows. Since resurfacing in the 2 dimensional model occurs in constant patches with a uniform thickness of 2 km, the number of partially embayed craters for these runs is greatly underestimated, and may be taken as a lower limit. For the ‘large patch’ solution branch, where the patch size is 0.1 with a period of 50 million years, the resulting crater population is manifestly not random

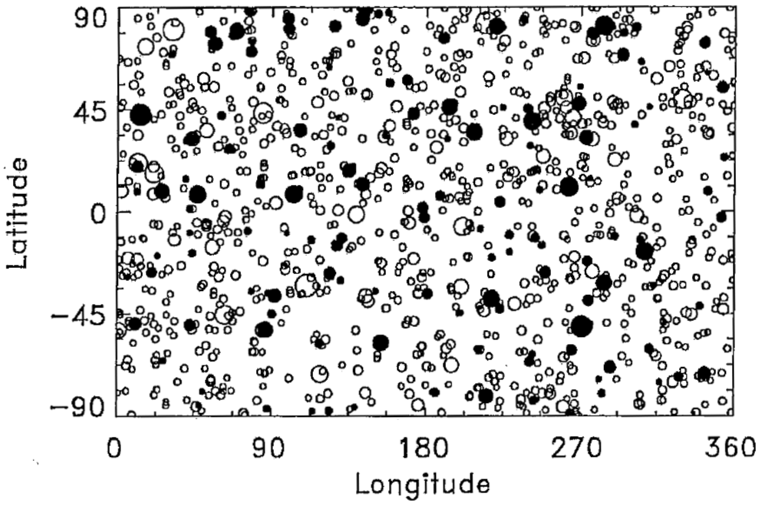

Fig. 3. Model results using parameters from the 2-D model of Phillips *et al.*, [1992], 'small patch' solution branch. The size of the area resurfaced per event is 0.0003 of the total area, and the period of periodic resurfacing is 150,000 years. Pristine craters are open circles, embayed craters (which represent 15% of the total population) are shaded.

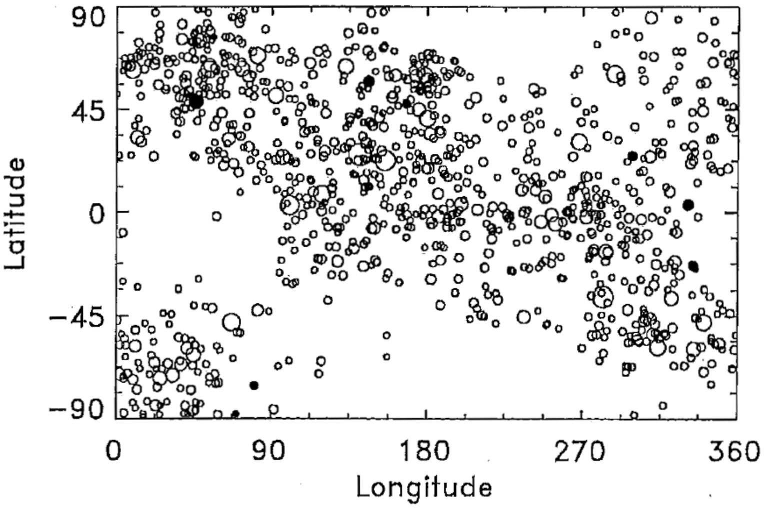

Fig. 4. Model results using parameters from the 2-D model of Phillips *et al.*, [1992], 'large patch' solution branch. The size of the area resurfaced per event is 0.1 of the total area, and the period of periodic resurfacing is 50 m.y. Pristine craters are open circles, embayed craters are shaded. Craters are not randomly distributed on the surface.

(Figure 4). By modeling the resurfacing process in 3 dimensions, we find that the equilibrium resurfacing model by Phillips *et al.* [1992] that is consistent with the observation of crater spatial randomness cannot also be consistent with the requirement of a small number of partially embayed craters. For this reason, it appears that a model that favors vigorous resurfacing in the past, followed by a low level of volcanic resurfacing, is far more consistent with the observed crater population.

Discussion

The Monte Carlo model presented here simulates the evolving surface of a planet by considering impact cratering and volcanic resurfacing. Impact cratering and volcanism are assumed to be spatially random, and occur uniformly in time. The initial conditions are simple: the planet is at first assumed to be free of impact craters and topography. Given these assumptions, and a consistent scheme for calculating the number of surviving pristine and modified craters, the constraints provided by the total observed crater population yield unique solutions to both the average resurfacing rate and the globally averaged surface age. We have shown (Figure 2) that the 3-D Monte Carlo model best simulates the total number of both surviving and partially embayed craters observed on Venus with a volcanic flux of about 0.37 km^3/yr. The resulting globally averaged surface age in this case is about 550 million years. This estimate is consistent with an earlier estimate for the upper bound of the volcanic flux (2 km^3/yr) based on the surface density of craters from Venera 15 and 16 [Grimm and Solomon, 1987].

Due to the constraint provided by the dearth of partially embayed craters, an equilibrium, regional resurfacing scenario, with the impact crater population in a steady state with resurfacing, is implausible. Resurfacing rates of approximately 2 km^3/yr or greater produce surfaces with the required number of craters that reach equilibrium in less than 1 billion years, but with far too large a proportion of volcanically modified craters. On the other hand, the model results presented here support the conclusion that a catastrophic resurfacing event that removed nearly all craters occurred on Venus and was followed by a low level of regional resurfacing for approximately 550 million years.

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