MODELLING THE CRATERING RECORD OF VENUS

by

Douglas Duane Dawson

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF PLANETARY SCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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entitled Modelling the Cratering Record of Venus

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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TABLE OF CONTENTS

TABLE OF CONTENTS-*CONTINUED*

TABLE OF CONTENTS-*CONTINUED*

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The images of the surface of Venus returned by the Magellan spacecraft show a cratering record unlike any other in the solar system. Multiple models of the geologic history of Venus have been proposed to explain this cratering record, including the "equilibrium resurfacing" model and the "global resurfacing" model.

I use a two-dimensional Monte Carlo simulation of crater emplacement and volcanic resurfacing to determine what sorts of cratering records would in fact be produced by these models. The equilibrium resurfacing model fails to produce a cratering record resembling the observations.

The global resurfacing model requires the specification of post-global resurfacing event history before it can be simulated by this program, but following appropriate specification, it did reproduce the observed cratering record. The global resurfacing model is thereby found to be a more satisfactory model than the equilibrium model.

The length of the tail end of the global resurfacing event is found to be of the order of 100 million years, subject to uncertainty in the impactor flux at Venus. The fraction of the planet resurfaced after the end of the global resurfacing event is found to be roughly 15-20%.

CHAPTER 1

INTRODUCTION

The atmosphere of Venus limits observations of the surface to either radar or lander imagery, but this has been sufficient to reveal a cratering record unique in the solar system. This cratering record has sparked substantial amounts of speculation about the geologic history of the planet. In order to understand what has gone on, however, we must understand just how the unusual features of the cratering record constrain that history. This work attempts to model how various resurfacing histories of Venus would have affected the cratering record, in order to give us a guide for selecting among them.

1.1 Motivation

Of all the data obtainable from a planet by means of simple imaging, the cratering record provides possibly the quickest guide to the geologic history of the planet. Differential crater densities show areas of geologic activity, overall crater density provides an estimate of the surface age, crater modification gives clues as to what surface processes have been at work, and individual craters can reveal properties of the near-surface crust (as in the rampart craters of Mars).

As will be discussed in Chapter 3, the cratering record of Venus is unique in the solar system, and as such implies a unique geologic history for the planet. Understanding the origin of this unique record provides us with insights into planetary geologic activity in general and may suggest lines of inquiry for other cratering records.

Since the recognition of Venus' unusual cratering record, multiple resurfacing histories have been proposed. Foremost among these are the idea that a constant resurfacing flux is keeping the crater population constant (the 'Equilibrium Resurfacing' model), and the idea that the entire planet was resurfaced relatively recently and that the planet has been more or less a production surface since that time (the 'Global Resurfacing' model). At a more fundamental level, several models of the internal processes of Venus have also been proposed, as discussed in section 3.3. Selecting the best choice from among such models requires a good understanding of just what the surface history must have been.

1.2 Philosophy—General Method Of Approaching the Problem

1.2.1 Monte Carlo versus Analytic

In a purely analytic approach to the problem, equations would be derived relating the time-dependent resurfacing rate to how many craters would be embayed, destroyed or left alone by lava flows. These equations could then be inverted to solve for what resurfacing history would have produced the current situation. In contrast to this, a Monte Carlo simulation would model the history by randomly emplacing craters and resurfacing events and seeing what cratering record resulted. This work is based on a Monte Carlo simulation; the apparent random distribution of craters suggests that such an approach may be applicable.

The original choice to do a Monte Carlo simulation instead of an analytic solution was made out of a desire to check the results of the simulations presented by *Phillips et al.* [1992], and due to a lack of obvious analytic approaches to take for the nonequilibrium cases of interest.

As of this writing, no analytic results have been published for any case other than the equilibrium resurfacing model. Since this case is tractable, an independent analysis was done to compare to the analysis of *Phillips et al.* [1992], and is included as Appendix A.

1.2.2 Two Dimensions versus Three Dimensions

The next issue to be confronted was the question of whether two or three dimensions should be modelled. In the two-dimensional model, the depths of craters and the thicknesses of resurfacing events and ejecta blankets are not modelled. At the time of the original decision, attempting a three-dimensional model would have required making many assumptions about such factors as typical lava flow thickness. More importantly, the addition of a third dimension increased the estimated run time of the program by orders of magnitude. It was felt that the statistical gain of being able to perform many runs was worth more than the increased knowledge of how individual craters were affected by individual resurfacing events.

The main uncertainty caused by using only two dimensions lies in the details of crater-lava interaction. Whether a given lava flow will actually be thick enough to completely cover a crater or whether it might fail to reach the top of the crater rim, for example, is not modelled. Instead, the area of a resurfacing event must be interpreted as the area which is covered by a thickness of lava sufficient to obliterate any crater. Similarly, the details of the effects of embayment are not modelled, so that the question of how many embayments are required to destroy a given crater is left open. This question is discussed in more detail in Section 4.3.1.

1.3 What Follows

The next chapter presents a discussion of the work by other authors on the cratering record and on the resurfacing history of Venus in general. In Chapter 3, I present a discussion of the cratering record (and its unusual features) as it is currently known. In Chapter 4, I discuss SimVenus, the program which was developed for this work. Chapters 5 and 6 discuss the results of SimVenus runs: Chapter 5 covers the equilibrium resurfacing model while Chapter 6 covers the general resurfacing model. Finally, in Chapter 7, I state my conclusions from this work. I was not able to uniquely constrain the resurfacing history of Venus, but I was able to show that the global resurfacing model is an acceptable framework for resurfacing histories while the equilibrium resurfacing model is not satisfactory. I was also able to produce likely figures for the length of the end of the global resurfacing event and area resurfaced since that event.

CHAPTER 2

Other Work

As one of the 'ancient' planets, the discovery of Venus is of course lost to antiquity. The earliest known mention of Venus is by the Babylonians, who recorded observations of it around 3000 BC (Huber). The earliest known telescopic study of Venus is more precise, however: Galileo's observation that Venus showed phases (Galileo, 1610).

Observations of the surface of Venus had to wait, however, for the development of radar. Pioneer Venus and Venera 15 and 16 each mapped portions of the surface from orbit, while ground-based measurements were made from Arecibo and Goldstone. During the late 1970's and early 1980's, many studies of the surface were made using these observations, but were limited by constraints of coverage and resolution. The true breakthrough did not come until the Magellan spacecraft reached Venus in late 1990.

2.1 Pre-Magellan Work

Venera 15 and 16 provided some of the very first radar images of the surface of Venus, but they mapped only the northern quarter of the planet (from near the north pole down to about 30° N latitude), at a resolution of 1 to 2 km. While this was sufficient to reveal a number of circular features, unambiguous identification proved elusive. Ground-based imagery had a similar resolution.

In their work with the Arecibo images, Campbell and Burns (1980) used the following criteria: "A feature is interpreted to be a crater when it can be described as a relatively circular area of low backscatter cross section surrounded by a high-contrast region of finite extent." Due to resolution limitations, the smallest crater that could satisfy these criteria would be about 20 km in diameter.

The first pictures of the surface of Venus [*Rumsey* et al., 1974] used the Goldstone tracking facility to measure radar reflectivity and altitude for a portion of Venus, centered at 2 degrees north and 38 degrees west. The most striking feature of this picture was a 160 km diameter crater at 2 degrees south latitude and 36 degrees west longitude, although Magellan revealed that no such crater existed (while the crater Alma is located near this point, it is only about 16 km in diameter). This map also showed a number of smaller, less clearly defined craters.

The first attempt to model the effect that the thick atmosphere of Venus would have on impactors was made by *Tauber and Kirk* (1976). Their model allowed for stony meteorites of 40 m radius and iron meteorites of 15 m radius to reach the surface, producing, respectively, a 300-400 m crater and a 150-200 m crater. In accordance with the cratering record, more recent work has pushed these minimum sizes up by an order of magnitude (see Section 2.4).

Masursky et al. (1980) noted that in the Pioneer Venus results, craters were seen only on the lowlands, suggesting that the highlands were significantly geologically younger. As discussed in Section 2.2.4, this observation was in error; even those workers who find a difference between the highlands and lowlands find the highlands to be somewhat older.

Solomon et al. (1982) calculated viscous relaxation times for Venus, and found that even if the surface of Venus were completely inactive, large features dating to heavy bombardment would have negligible relief at present. They also found that very large-scale features such as Atalanta Planitia could only last a few hundred million years and hence were very unlikely to be impact basins. The Magellan dataset has confirmed that the very large-scale features do not appear to be impact basins. No evidence has been found of craters which have relaxed to the extent predicted for features of nearly heavy bombardment age.

2.2 Stratigraphy

Comprehensive stratigraphic analysis of Venus had to wait until extensive geologic mapping had been done. The first full treatment of the subject was by *Basilevsky et al.* [1997], but the critical fact as regards this work was first published by some of the same authors in *Collins et al.* [1996]. This fact is that the earliest resurfacing seen (the emplacement of the plains units) appears to have embayed somewhere between 13 and 18 craters; the remaining embayments appear to have occurred at later times.

The individual craters which were identified as having been embayed by plains emplacement were not listed in *Basilevsky et al.* [1997]. However, a personal communication from R.G. Strom, one of the authors on that paper, has allowed me to include Figure 1, which shows the location of the plains-embayed craters (as well as the other flooded craters, which were embayed by later flows).

One important result which is obvious from this figure is that the later-embayed craters are quite obviously non-randomly distributed. Instead, they are concentrated in the region between 0° and 30° north latitude and 180° and 300° longitude. This region is also the center of most rifting activity on Venus.

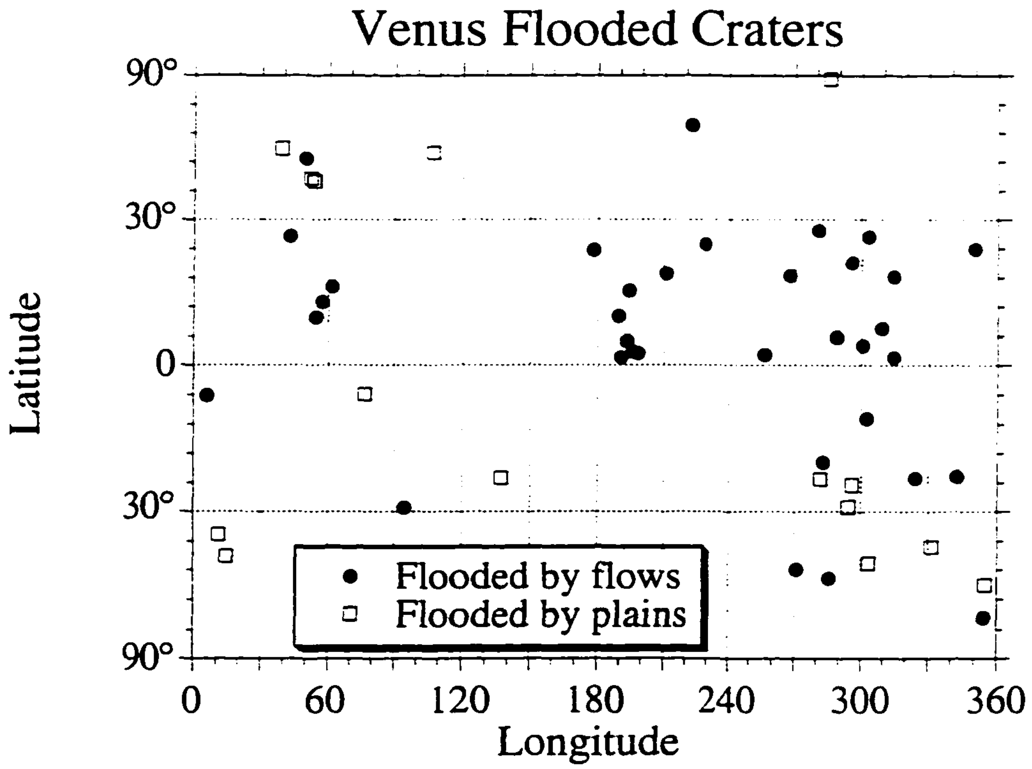


Figure 1. Map of all flooded craters. The symbol used distinguishes between those identified as being embayed by the emplacement of the plains and those embayed by later flows.

2.3 Interior Process Models

A considerable amount of work has been done on modelling the processes going on in the interior of Venus. The motivation of this work and of SimVenus are closely interrelated: it is hoped that by constraining resurfacing histories more closely, it will be possible to distinguish between interior process models, and many of the interior process models were first motivated by the general global resurfacing model.

In one family of models, there is extensive recycling of the lithosphere; this is sometimes referred to as "plate tectonics," though it may substantially differ from that of the Earth. In the model of *Arkani-Hamed et al.* [1993], oscillatory behavior in the convection of the mantle leads to alternating periods of very high recycling and periods of quiescence; while the current surface may simply be in a quiescent mode, their simulations suggest that an early oscillation may have disappeared due to secular cooling.

Turcotte [1993] proposes similar alternation between active and quiescent periods. In this model, the thermal boundary layer cools and thickens during the quiescent periods until it becomes thermally unstable. The subsequent detachment of the layer initiates the active phase of recycling.

Parmentier and Hess [1992] propose a superficially similar model, in that recycling is triggered by the detachment of a crustal layer. However, in their model, the important factor controlling the instability of the layer lies in the chemical differentiation in the lithosphere.

2.4 Other Lines Of Evidence

There have been a number of other proposed lines of evidence for estimates of the rate of volcanism on Venus. In general, while some of them are suggestive of much higher rates than this work produces, nothing conclusive has been produced, and many of them are easily compatible with this work.

Robinson and Wood [1993] ascribe anomalous emissivity values in some regions of Venus to recent volcanism. They identify Maat Mons as the most recent site of volcanism; however, they are careful to note that our current data does not allow for determining just when this activity occurred, nor for how long.

Similarly, recent volcanism has been proposed as an explanation for varying sulfur dioxide levels in the atmosphere of Venus. Measurements in the late 1970's by *Barker* [1979], *Stewart et al.* [1979] and *Conway et al.* [1979] showed levels of SO_2 above the clouds that were far higher than the upper limits implied by the negative results of *Owen and Sagan* [1972]. Pioneer Venus observations made from 1978 to 1986 revealed a decline back towards those implied upper limits (*Esposito* [1988]). *Esposito* [1984] proposed that volcanism can propel sulfur dioxide above the clouds, where it then is removed on timescales of years; this does not explain a similar decline in *in situ* measurements.

Fegley and Prinn [1989] note that the sulfuric acid cloud cover needs a source to replenish losses due to reactions with the surface and state that volcanism is the most likely. Modelling the expected loss rate and expected sulfur content of lava, they estimate that 0.4 to 11 km^3 of material is erupted onto the surface per year, with a preferred value of ~1km^3.

CHAPTER 3

VENUS: THE CRATERING RECORD

The cratering record of a body gives us one of the quickest and easiest handles on that body's geologic history. It requires nothing more than images of the surface, and while high resolution is better, even fairly low resolution is fairly useful. On Venus, however, the atmosphere long prevented any imaging at all, Venera 15 and 16 only covered roughly the northern quarter of the surface at 1 to 2 km resolution (similar to the resolution of ground-based radar, which failed to even accurately identify craters (as discussed somewhat in Chapter 2). The data returned from Magellan, covering more than 98 percent of the surface at a resolution of approximately 100 meters, finally allowed us to determine that Venus has a very unusual cratering record indeed.

3.1 Definition Of The Cratering Record

In most cases, for most bodies in the solar system, the term "cratering record" is simple to define: the collection of all impact craters on the body, together with their ejecta. On Venus, however, there are a number of additional features that are believed to be impact-derived--splotches, halos, and parabolas, discussed in more detail in Section 3.3. Probably resulting from the interaction of an impact shock with the surface and atmosphere, these features cover a significant portion of the planet (compared to the area of the craters proper) and can be an important factor in constraining the geologic history of Venus. They are therefore included in the term "cratering record" as used in this work, except where specifically noted otherwise.

The primary basis of this work is the USGS/University of Arizona crater database (usually referred to as simply the USGS database). Crater numbers, diameters, etc. are from this database. This database is subject to continued revision; for example, while all of the SimVenus runs described in this work use a total crater number of 940, the actual most current count is 950, as described below. The Herrick/Phillips database disagrees with the USGS database in many important respects, including most significantly total number of craters (lower than the USGS number) and number of embayed craters (higher than the USGS number). This is discussed in more detail below.

3.2 Anomalous Features Of The Cratering Record

Even before Magellan arrived at Venus, it was expected that the cratering record would turn out to be unique in the solar system. The existence of a thick atmosphere and the high surface temperature alone were expected to have a major effect on the formation and preservation of craters. Still, when the cratering record was at last revealed, it proved to have a number of unexpected characteristics. Most, if not all, of these anomalous features have a direct effect on this work.

3.2.1 Low Number Of Craters

As of the most recent count (*Schaber et al.* [1998]), 950 primary impact craters have been identified on the surface of Venus. Of the other planets and satellites whose surfaces have been observed, most show more craters than we have been able to count. The only places where fewer craters are observed are Earth, Io, and Europa; Venus shows no sign of being very similar to any of those bodies.

The Question Of Volcanic Features

Herrick et al.[1995] state that on the order of 50 features identified as impact craters in the USGS database are actually of volcanic origin, while another 150 or so are of possible volcanic origin. This is reflected in the Herrick/Phillips database and is the source of much of the disagreements between different workers. The disputed features have been reexamined and are still believed to all be impact craters (R.G. Strom, personal communication).

3.2.2 Size Distribution Of Craters

Most bodies in the solar system show a standard size distribution of craters, or, more precisely, show a population composed of two standard size distributions. These two standard size distributions correspond to the period of heavy bombardment and the time since the end of heavy bombardment ("modern" size distribution). Venus is not expected to show any craters from the period of heavy bombardment; not only would they have been erased under both major resurfacing history models, but from the work of *Solomon et al.* [1982] (see section 2.1), they would be expected to have completely relaxed by the present. Figure 2 shows a comparison of the diameter/density distribution of Venus with the "modern" size distribution, here taken from the young areas of Mars; young areas on Mercury and the Moon show similar size distributions. Figure 3 shows the diameter/density distribution of Venus craters.

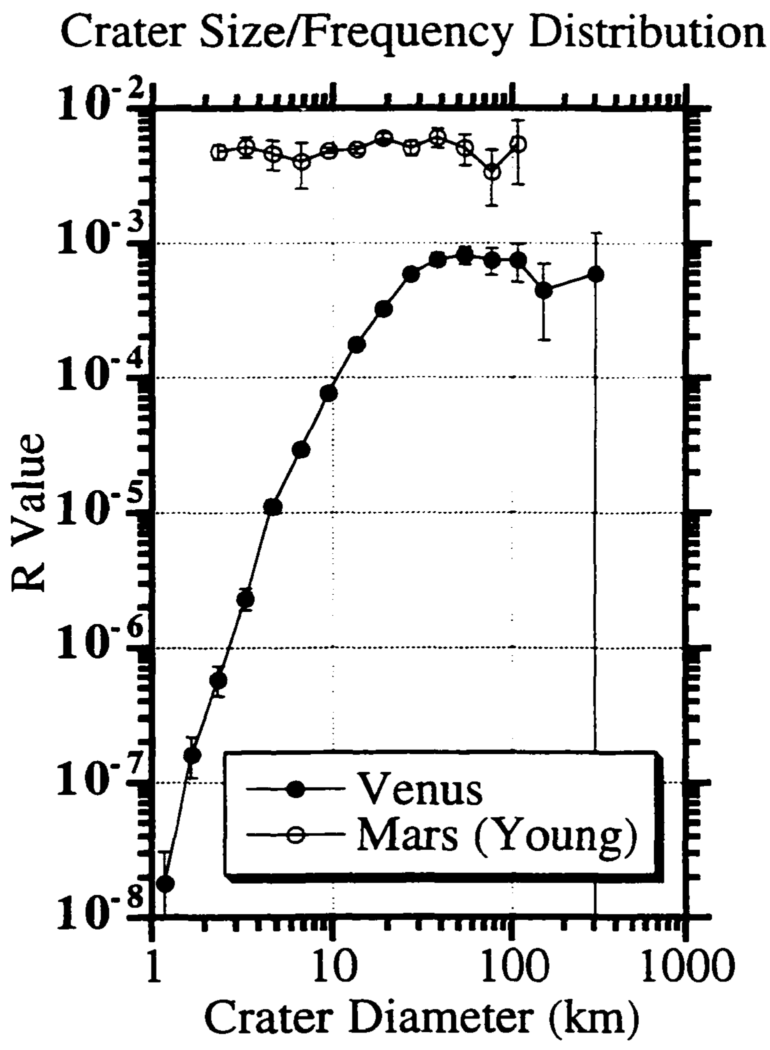


Figure 2. Crater diameter/density distribution of Venus and Mars. The R value is the ratio of the observed distribution function to the function $N=D^{-3}$, where N is the number of craters per unit area and D is the crater diameter.

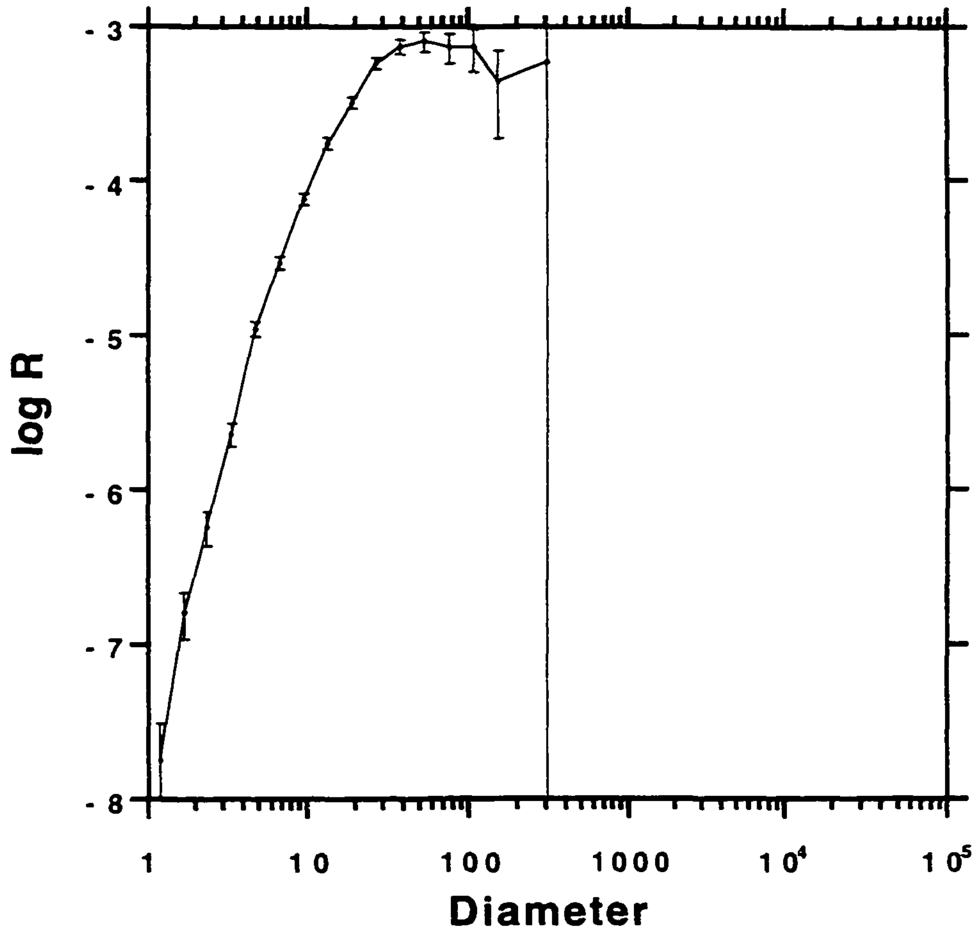


Figure 3. Crater diameter/density distribution for Venus. All diameters are from the USGS database. The R value is defined as in Figure 2.

As can be seen, for craters greater than about 32 km in diameter, the Venus crater size distribution agrees very well with the "modern" size distribution, showing no evidence of the "heavy bombardment" size distribution. For craters less than 32 km in diameter, the Venus crater size distribution shows a falling off with decreasing size, as opposed to the great increase of both the "modern" and "heavy bombardment" size distributions. Finally, Venus shows almost no primary impact craters smaller than 1.3 km in diameter, despite imagery resolution that would allow such craters to be observed.

This altered size distribution is perhaps the best understood of the unusual features of the cratering record. Even prior to Magellan, it was predicted that Venus' thick atmosphere would have a screening effect, blocking all sufficiently small impactors, having no effect on sufficiently large impactors and blocking some of intermediate size. Analyses of this effect have been done by *Phillips et al.* [1992], *Herrick and Phillips* [1994a], *Zahnle* [1992], and *McKinnon et al.* [1997].

3.2.3 Pristine Condition Of Craters

The condition of individual craters on Venus ranges from pristine to heavily modified, both from volcanism and tectonism. Taken as a group, however, they are remarkably unmodified. As of the last classification, 781 are classified as pristine, 137 as tectonically modified, 5 as modified by other impact craters, and 50 as volcanically modified. This adds up to more than 950 due to some craters being both tectonically and volcanically modified. Table 1 is a list of specific classifications.

Such a low degree of modification is unique in the solar system. The cratering records of other bodies show many craters along the entire spectrum of modification from pristine to barely detectable "ghost" craters. Despite the modified craters listed above, however, no "ghost" craters have been detected on Venus; even the heavily modified craters are clearly distinguishable.

This low degree of tectonic and volcanic modification has profound implications for the planet's geologic history. The resurfacing rate must have been either very low over the age of the surface, or the resurfacing process must in some way avoid modifying the craters.

Figure 4 shows a typical pristine crater.

Description	Database Code	Number
Pristine	p	781
Slightly Fractured	f1	101
Heavily Fractured	f2	22
Greatly Disrupted	f3	10
Fractured By Compressive Fault	fc	4
Only Ejecta Embayed By Volcanic Lava	vm	22
Ejecta and Floor Heavily Embayed By Lava	vh	15
Flooded By Lava Plains (possible GRE)	vp	15
Partly Covered By Impact Ejecta From Adjacent Crater	e	5

Table 1: Breakdown Of Crater Modification Classes. This is based on the USGS/University of Arizona database.

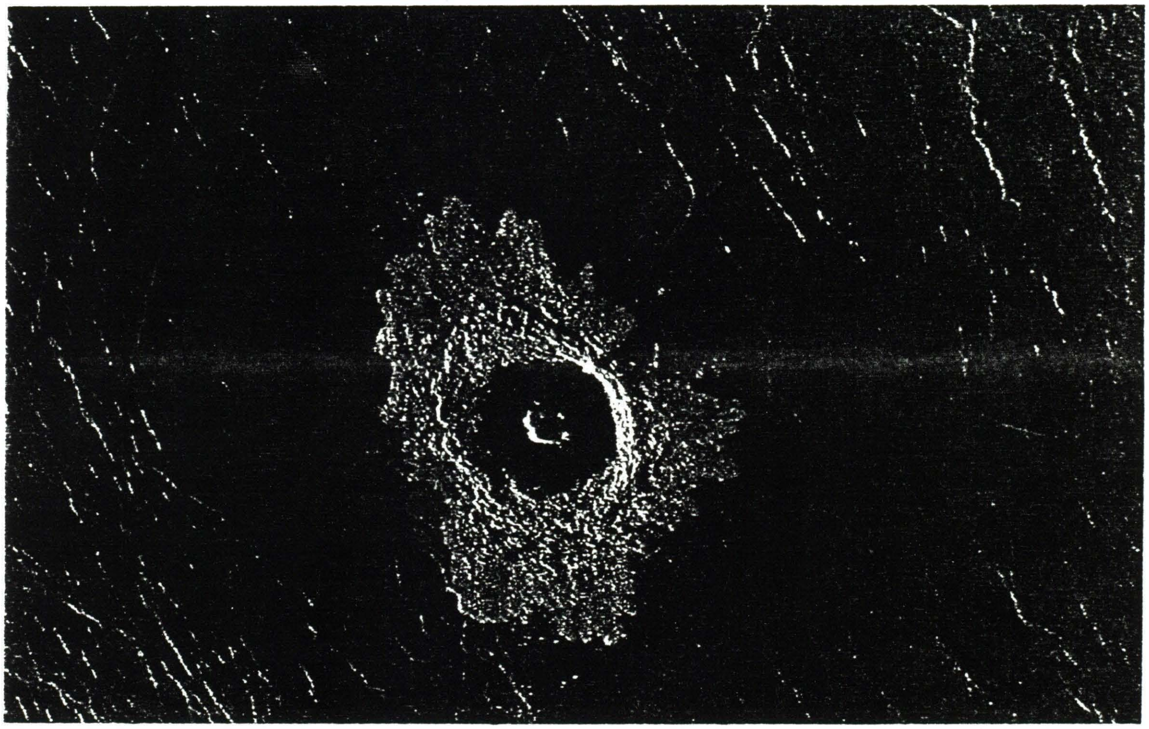


Figure 4. A typical pristine crater. This crater is named Godiva, has a diameter of 30.7 km, and is located at 56.1° S latitude and 251.6° longitude.

As a side note, no craters are classified as being recognizably altered by aeolian effects. This is not unexpected, given the extremely low surface wind speeds believed to be typical of Venus (0.5 to 1m/s^2, according to *Counselman et al.* [1979]).

The Question Of Embayment

The number of embayed craters listed above is disputed. For example, *Herrick and Phillips* [1994a] reports about 60 embayed craters, while *Herrick et al.* [1995] reports 74. As with the suggestion of volcanic features above, the proposed additional embayed craters have been reexamined and still judged to be nonembayed (R.G. Strom, personal communication). Figure 5 shows a typical undisputed embayed crater.

These workers suggest, in fact, that all dark-floored craters may be partially filled with lava, possibly as a result of impact-caused volcanism. This idea is supported by *Sharpton's* [1994] result that dark-floored craters are typically several hundred meters shallower than bright-floored craters of comparable diameter. However, even if true, this has only a trivial effect on the overall resurfacing history of Venus, as the amount of lava produced falls far short of that needed to breach the crater rim. It is possible to postulate that many craters produce enough lava to obliterate

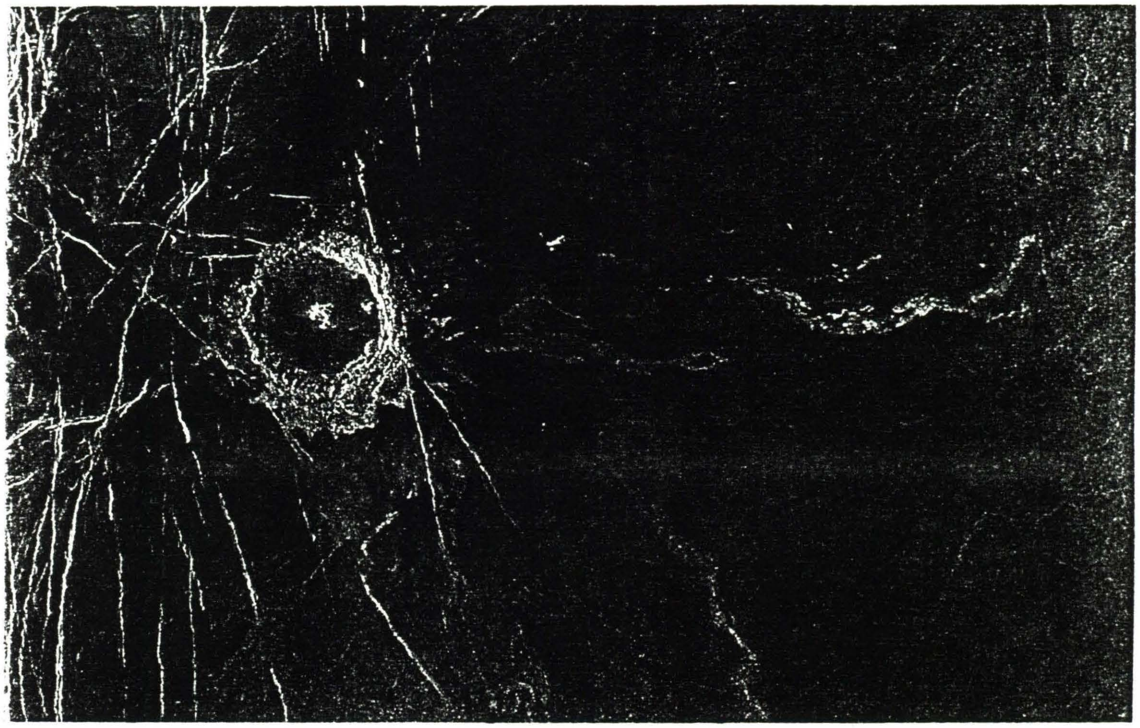


Figure 5. A typical embayed crater. This crater is named West, has a diameter of 28.8 km, and is located at 26.1° N latitude and 302.9° longitude.

themselves but not enough to substantially affect other craters, but in that case we would expect to see a number of craters in the middle range as well, with enough lava to breach the rim but not enough to obliterate the crater, and no such craters are observed.

A possible partial explanation lies in the fact that a number of calculations have shown that impacts on Venus should produce more impact melt than similarly sized impacts elsewhere, due to both higher surface temperature and higher surface gravity (e.g., *Ivanov et al.* [1986], *Phillips et al.* [1991], *Vickery and Melosh* [1991]).

3.2.4 Uniform Distribution Of Craters

To an altogether remarkable degree, the 950 impact craters are distributed randomly across the surface of Venus. The variations in crater density from one are to another are within the expected range for a purely random process. This randomness has been measured and analyzed by a number of workers, including *Strom et al.* [1992], *Phillips et al.* [1992], and *Turcotte et al.* [1998], with the conclusion that the distribution cannot be distinguished from random.

It must also be noted that this applies only for the craters taken as a whole; various subdivisions (such as modified versus unmodified, or large versus small) may not all be randomly distributed. For example, *Kreslavsky and Muinonen* [1996], using the Herrick/Phillips database, report that the lowland areas of Venus suffer from a relative deficiency of large craters, while the highland areas have something of a relative excess of large craters. Other workers (*Strom et al.* [1994]), using the USGS database, feel that this apparent deviation lies within the stochastic limits of a purely random distribution. For another example, the embayed craters of the USGS database are clearly distributed in a nonuniform fashion.

3.3 Crater-Associated Features

While ejecta blankets are a common feature associated with craters, seen nearly universally, the Venus cratering record contains many features not seen elsewhere: parabolas, halos, splotches, dark margins, and ejecta flows. As noted above, they are areally extensive (with the exception of the dark margins) and need to be considered along with the craters proper, but the mechanisms of their formation and destruction are not yet well understood. In general, they are believed to be due to the interaction of the impact event with the Venus atmosphere and to be very thin and relatively short-lived features.

3.3.1 Parabolas

Possibly the most dramatic of the crater-associated features are the parabolas, first described and catalogued in *Campbell et al.* [1992], with some additional examples listed in the USGS database, and in *Schaller and Melosh* [in press]. 59 of these parabolic-shaped features, hundreds of kilometers in extent, have been identified on the surface of Venus. An additional 10 approximately circular features, similar to the parabolas in many respects, have also been identified.

No instances have yet been definitely found of features superimposed on a parabola (one worker has stated that an embayed parabola has been seen, but no success has been achieved in finding this feature [R.G. Strom, personal communication]), suggesting that they are among the youngest features on the planet. These features are also notable for their orientation: with seven exceptions, they are all roughly oriented E-W, opening towards the west. Each parabola has a crater located near the apex, on the axis of symmetry.

Figure 6 shows a typical parabola.

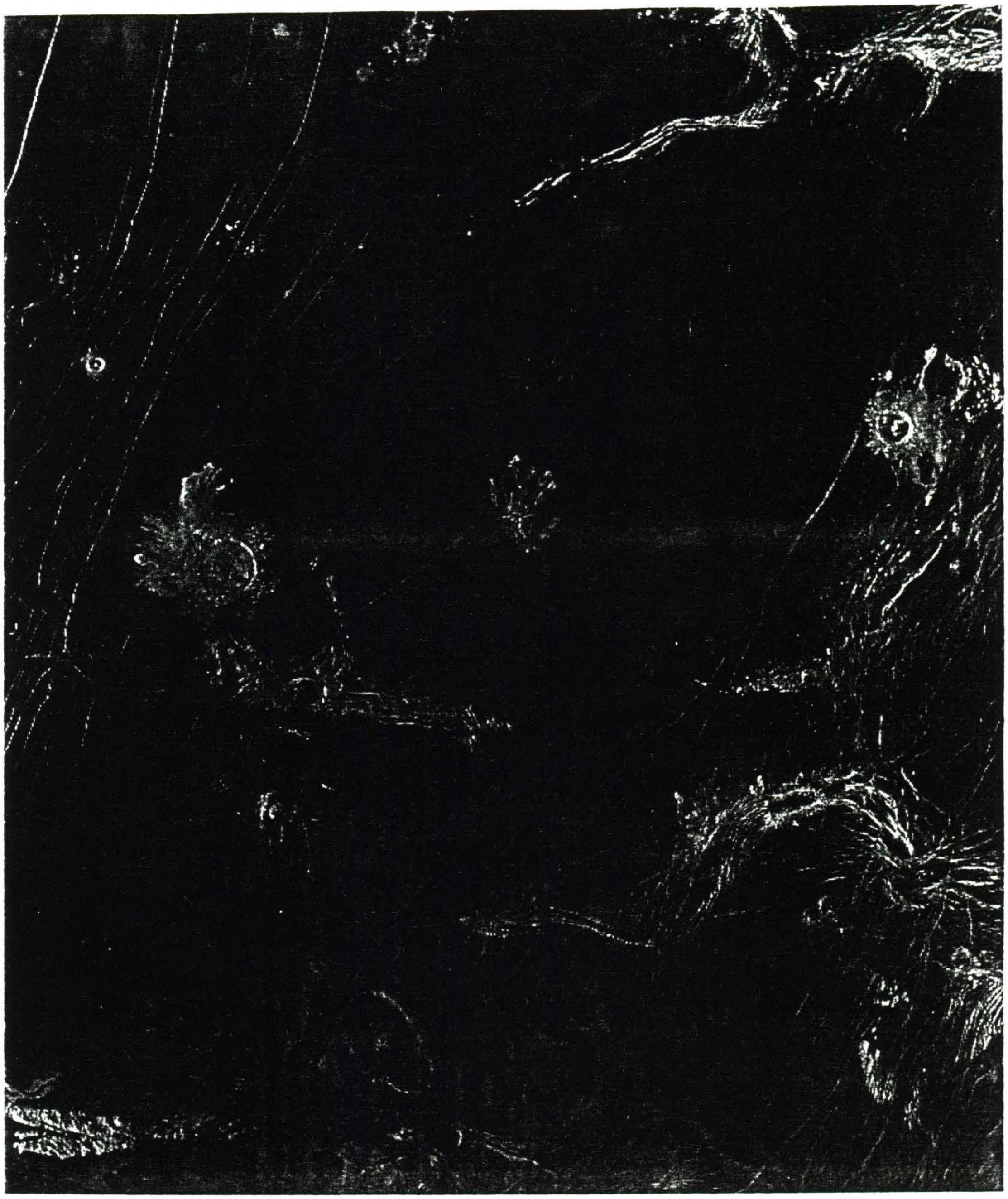


Figure 6. A typical parabola. The crater is named Stuart, has a diameter of 68.6 km, and is located at 30.8° S latitude and 20.2° longitude.

Work on modelling the emplacement of the parabolas has been done by *Vervack and Melosh* [1992] and *Schaller and Melosh* [in press]. This model states that an impact produces a large number of very fine particles, many of which are launched entirely out of the atmosphere. As the particles reenter the atmosphere, they are carried westward by the high-altitude Venusian winds and they settle out, forming a thin layer, generally between 2 cm and 20 cm in thickness.

If this mechanism is correct, then it should be possible for even the low surface wind speeds on Venus to eventually remove the parabolas. Even if all impacts form parabolas, an assumption supported by the results of *Schaller and Melosh* [in press], only the youngest craters will still have them. Using this assumption suggests that, on average, parabolas are completely removed on a timescale of roughly 60 cratering intervals or 70 if the ellipses are included as well. Combining this with estimates of the cratering flux at 1 crater roughly every 400,000 years (see Section 3.4) gives a lifetime of 24-28 million years, with a factor of two uncertainty either way.

Parabolas have a significant constraining effect over Venus' recent geologic history, as they tend to have an order of magnitude more area than their associated crater and, apart from the apocryphal example mentioned above, show no embayment whatsoever. The constraint this places on models of the resurfacing history is referred to by this work as the parabolic criterion and is discussed in Chapter 5.

3.3.2 Halos

Another set of impact-related features are the so-called "crater halos" or simply "halos." Certainly, they share many characteristics. These are extended features that form concentric circles around some craters. They can be either darker than their surroundings, brighter, or both: many consist of a series of alternating bright and dark rings. Figure 7 shows a typical halo (at the right of the image).

While at first, only a relatively small number were identified, more and more haloed craters have been identified by enhancing the contrast on SAR images of the surface. Halos tend to be smaller than parabolas, so it may be that some or all of the parabolas are superimposed on hidden halos.

While, as with parabolas, halos are believed to be a result of the interaction between the impact process and Venus' atmosphere, the details of formation are felt to be completely different. While parabolas involve the deposition of fine impact ejecta, halos are thought to be due to the interaction of the shockwave from the impactor with the surface (see, e.g., *McKinnon et al* [1997]), though *Schultz* [1992] proposes that they are due to settling of impactor material which has been crushed during atmospheric entry. Multiple mechanisms have been proposed, including breaking of small surface rocks and forcing of atmospheric gases into rock pores.

Also as with parabolas, halos are much more areally extensive than the craters they are associated with, and provide a proportionally stronger constraint on the geologic history of Venus. No instances of embayed halos have been recorded. The constraint this puts on modelling the resurfacing history is referred to in this work as the halo criterion, and is discussed in Chapter 5.

3.3.3 Splotches

Almost certainly related to halos are the features known as “splotches” or, occasionally, “craterless halos”. As their alternate name implies, they appear to be halos as described above, except that they lack a crater at their center. The formation mechanism for splotches is believed to be similar to that of a halo, except that the impactor involved is either destroyed in midair, or slowed below the velocity needed to form a crater. On the order of 400 splotches have been identified, but this record is known to be very incomplete. Figure 7 shows a typical splotch (on the left).

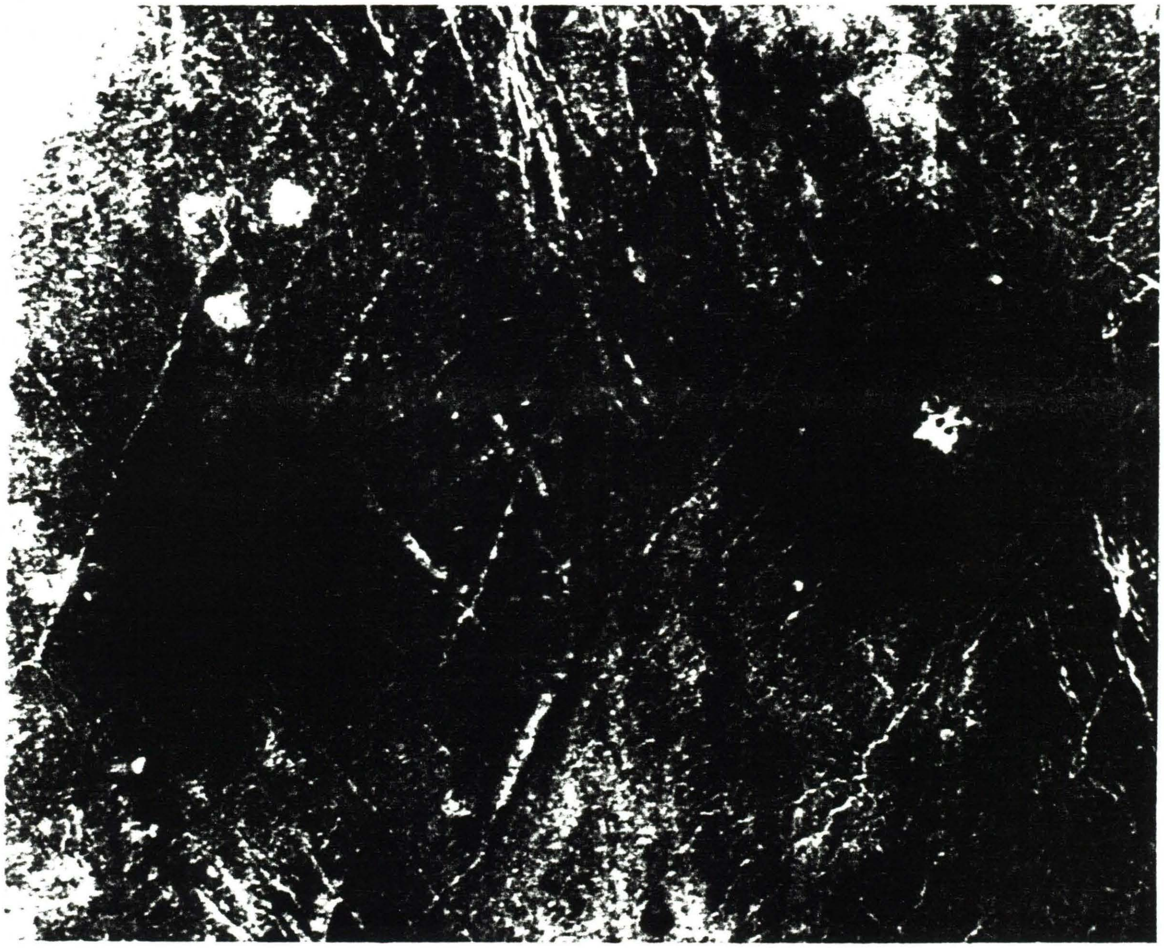


Figure 7. A typical halo and a typical splotch. On the right is a halo surrounding an unnamed crater named located at 20.7° south latitude and 338.7° longitude. On the left is a splotch. This image emphasizes the similarity of splotches and halos.

Splotches are distributed in a notably nonuniform fashion. Far more splotches are apparent at low latitudes than at high latitudes. The cause for this is probably an observational effect; perhaps at the observation angles used for high latitudes, splotches are much less visible. Also, splotches are not readily apparent in rough terrain.

Splotches pose an interesting question for efforts to model the history of Venus. Their production rate is much more poorly constrained than that of craters; unlike parabolas, they are not tied to craters. This lack of a production rate also makes it very difficult to closely estimate their lifetime, though we can place outer bounds.

At one extreme, if splotches are as durable as craters (highly unlikely), then it is reasonable to emplace splotches for the entire duration of a simulation; this would incredibly constrain any model. At the opposite extreme, if they last only a few hundreds of thousands of years or less, they provide almost no constraint whatsoever. Between the extremes, if their lifetime is similar to that of a halo, then they should be emplaced simultaneously with the haloed craters; this constrains the later history of Venus but not the earlier portion.

While some previous work (*Strom et al.* [1994]) was done including varying number of splotches, the questions described above suggest that the meaning of that work must be considered highly questionable at best. In particular, that work made no attempt to account for the irregular distribution of splotches, and assumed that splotches lasted until destroyed by resurfacing (highly unlikely).

3.3.4 Dark Margins

Dark margins were first described in *Schaber et al.*[1992], and not much work has been done on them since. As their name suggests, they are dark features that run around the margins of many impact crater ejecta blankets. They were originally combined with halos, but the term seems to have evolved to represent only features that are very limited in size. As they are not areally extensive, they have little significance to this work.

3.3.5 Ejecta Flows

Many craters on Venus show bright outflows extending from them. These flows are associated with and intermingled with the usual ejecta blanket, but stretch for distances of up to 600 km. Figure 8 shows a typical crater with extended bright ejecta flow. It is commonly felt (e.g., *Schaber et al.* [1992], *Asimow and Wood* [1992], *Schultz* [1992]) that they contained impact melt and hot gases during formation, but the exact nature of the

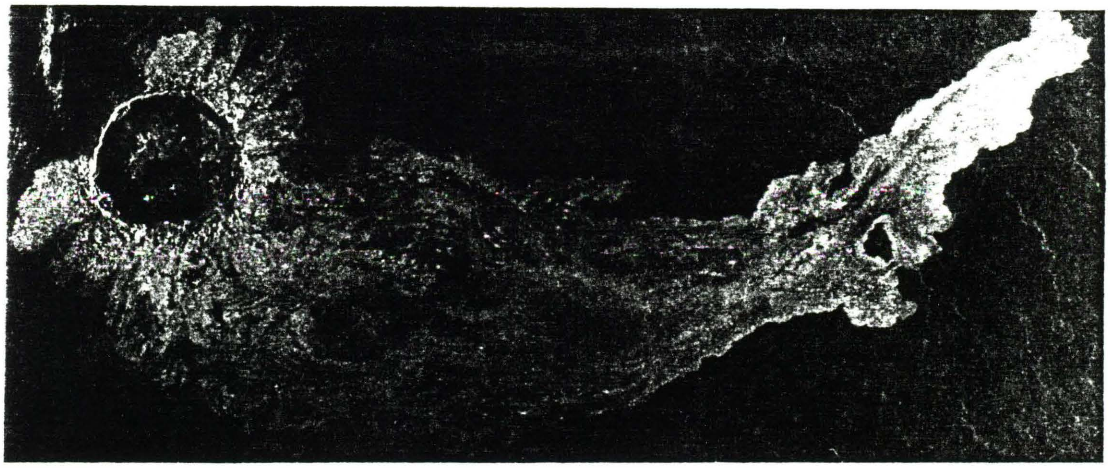


Figure 8. A typical bright ejecta outflow. The crater is named Addams, has a diameter of 87 km, and is located at 56.2° S latitude and 98.9° longitude.

formation and emplacement mechanisms is still subject to debate. The enhanced melt production of craters on Venus (as discussed in Section 2.2.3) is believed to contribute to their formation.

Besides their length, they are remarkable for their small thickness (no relief is detectable at their margins) and for their interactions with topography. At considerable distances from their craters, the flows seem to have been relatively slow, with few unusual features and following the local gradients. Near the source craters, however, outflows produce distinct channels and streamlined islands, and sometimes go substantially uphill, suggesting considerable velocities were involved.

While a considerable amount of work has been done on bright ejecta flows, their importance to this work lies in their area, thinness and brightness. Their lack of relief means that any lava at all could cover them with ease, while their brightness allows this to be readily detectable. Unlike halos, parabolas and splotches, ejecta flows should be resistant to aeolian removal but like them, ejecta flows can be areally extensive and thereby constrain the resurfacing history.

3.4 Cratering Record Criteria

Since the purpose of this work is to determine what resurfacing history could reproduce Venus' cratering record, we can restate the unusual properties of the observed record as a set of criteria. We can then apply these criteria to the results of any given resurfacing history to decide if it is a suitable model. This was done as early as *Schaber et al.* [1992] for a set of three criteria (referred to in this work as the 'basic criteria'), but later consideration revealed three additional criteria (referred to here as the 'extended criteria'). In addition, stratigraphic analysis (described in section 2.2) gives additional evidence which can be applied in what will be referred to as the 'stratigraphic criterion,' though it is the loosest of the criteria.

3.4.1 The Basic Criteria

As first described in *Schaber et al.* [1992], the three basic criteria are that: 1) the model must produce a low total number of craters (~940); 2) the model must produce a uniform distribution of craters: and 3) the model must produce a low number of volcanically embayed craters (~50). These criteria have been more or less accepted by most workers in this area, subject to debates over the exact number of craters, the exact degree of randomness in the distribution, and the exact number of embayed craters, as discussed in Section 3.2, above. These are the criteria that I have used in all my work prior to this work; only recently has SimVenus been modified to allow the extended criteria.

3.4.2 The Extended Criteria

Each of the extended criteria is based on the fact that none of the extended surface features believed to be impact-derived (parabolas, halos, and splotches) show any embayments. These features are quite areally extensive and can impose significant constraints on the resurfacing history. While these facts were recognized early on, they have not been applied to the problem until this work.

The Parabolic Criterion

As discussed in *Campbell et al.* [1992], the parabolas seem to be the youngest features on Venus. Stratigraphically, they are superposed on all other terrain features. None show any evidence of volcanic modification at all, with the possible exception of one feature; as mentioned in section 3.3.1, while one worker has reported an embayed parabola, this remains unconfirmed. This puts a powerful constraint on the resurfacing history of Venus: the resurfacing rate for the recent past must be quite low. The parabolic criterion is that the model must not embay any parabolic features; for purposes of this work, this will be considered equivalent to an average number of embayed parabolic features less than 0.5.

The Halo Criterion

Much like the parabolas, no halos are known to have been embayed. Halo craters are believed to be generally older than the parabolas but younger than craters without halos. If this is true, then the absence of embayed halos means that the period of very low resurfacing implied by the parabolic criterion must extend further into the past.

In parallel with the definition of the parabolic criterion, the halo criterion is that, on average, no halos be embayed; for purposes of this work, this will be taken as having less than 0.5 halos embayed.

SimVenus did not have the capability to keep track of halos separately until the Full Sequence runs. However, this is not important for the Craters Only runs, since they disregarded halos completely. While the Extended Ejecta runs did use halos, they mixed them in with the non-halo craters; since halos comprise about one-third of all craters, it would be expected that they should make up about one-third of embayed craters as well, were all else equal. Since halos are much larger than the craters themselves, it is likely that a significantly larger fraction of the embayed features will be halos; thus, any of the Extended Ejecta runs would almost certainly fail the halo criterion.

The Splotch Criterion

As discussed in section 3.3.3, the splotches form a very problematic portion of the cratering record. While, as with the parabolas and halos, there are no observed embayed splotches, the questions of when, where, and how frequently the splotches should be emplaced remain open. Nevertheless, it is still possible to define a splotch criterion modelled on the parabolic and halo criteria: less than 0.5 splotches should be embayed, on average.

Splotches were not included in any of the size sequences described earlier in this work. Instead, a special set of runs was made adding splotches to selected Full Sequence runs, with splotches emplaced in parallel with halos and parabolas (that is, with the assumption that splotches have a lifetime similar to that of halos since they are believed to form by a similar mechanism). The results of these runs are described in Section 5.3.3.

3.4.3 The Stratigraphic Criterion

As was discussed in section 2.3, stratigraphic evidence suggests that only 13-18 or so of the embayments occurred during the formation of the plains units, the oldest resurfacing in the record. This can be used as a criterion by assuming that the later embayments happened significantly later and spread over a longer period of time. The lack of any absolute dating makes application of this criterion highly dubious, however.

3.5 The Cratering Flux

In order to use the cratering record to provide us with an estimate of an absolute age of Venus' surface, it is necessary to estimate the rate at which craters are produced. As with other bodies in the solar system, the first step in this process is to produce an approximate flux of impactors that can hit Venus. Unlike most other bodies, an additional step is required for Venus: estimating how many of those impactors would fail to penetrate the atmosphere.

The primary work on calculating the cratering flux for Venus was done by *Shoemaker et al.* [1991], who originally derived a rate of $(3.3\pm1.8) \times 10^{-15}$ km^{-2} yr^{-1} for craters ≥ 20 km diameter on Venus, using a rough correction for atmospheric deceleration. Multiplying by the surface area of Venus and correcting for the observed size distribution on Venus gives an estimated cratering interval of about 230,000 years.

Subsequent to that time, a number of workers have used the impactor flux estimates of *Shoemaker et al.* [1991] with improved atmospheric interaction models (as discussed in Section 3.2.2), for example *McKinnon et al.* [1997]. That model also includes changes in crater scaling, and ends up producing cratering rates substantially lower than those of Shoemaker et al., producing a nominal surface age of 750 Ma instead of the 300 to 500 Ma results produced from the earlier estimate.

At this point in time, it is difficult to determine which sets of assumptions are more appropriate. In this work, a rate of one crater (of any size) produced every 400,000 years on average is used. This is the only tie to an absolute age in the SimVenus code, and all else scales with it. If, for example, an 800,000 year interval were eventually found to be more accurate, then all the times mentioned in this work would be doubled.

CHAPTER 4

TOOLS: THE SIMVENUS CODE

A number of possible cratering and resurfacing histories have been proposed to explain the unusual features of Venus' cratering record described in Chapter 3. In addition to analytic arguments as to whether or not a particular history could produce the observed features, so-called "Monte Carlo" simulations have been used as well. One such effort forms the core of this work.

SimVenus: Description Of The Program

"SimVenus" is the name given to the code developed to model the effects various resurfacing histories may have had on the cratering record of Venus. It was originally written in an effort to duplicate the somewhat puzzling results of *Phillips et al* [1992] with regards to the equilibrium resurfacing model (see Section 5.2). Later, it was expanded and adapted to test consequences of the global resurfacing model (Section 5.3). It was written entirely by the author in C.

4.1 Overview

SimVenus begins with a blank planet, with no features. A clock is advanced for a predetermined duration. At regular intervals, an impact feature is emplaced. At other times, a resurfacing event is emplaced. Whenever a resurfacing event is emplaced, every impact feature is checked to see whether this event would embay or remove it. At the end of a run, the number of surviving pristine, embayed, and destroyed impact features are counted. SimVenus repeats the process for a predetermined length of time and averages the results, printing the resulting numbers to an output file.

4.1.1 Feature Size Databases

SimVenus uses a number of databases to provide sizes for various emplaced features. For impact craters and halos, the USGS/University of Arizona database is used. For parabolas, the areas measured by *Campbell et al.* [1992] are used to calculate equivalent radii; this is supplemented by direct measurements for parabolas discovered after the publication of that work. For resurfacing events, the areas of volcanic features measured by *Head et al.* [1992] were used to calculate equivalent radii.

4.2 Impact Feature Emplacement

Impact features are emplaced at fixed intervals. The interval currently in use is 400,000 years, based on estimates of the cratering flux at Venus (see Section 3.4). This is the only connection to an absolute age in the code. If a different impact interval is used, all resulting times scale linearly.

When an impact feature is emplaced, a location is randomly determined. The longitude is determined by simply using a standard linear random number generator. The latitude is determined by using the linear number random generator to produce a number between 1 and -1 which is taken to be the sine of the latitude. This method produces an equal area distribution over the planet.

4.2.1 Size Of Emplaced Impact Features

A size for the feature is randomly chosen from a list of feature sizes (the databases used to provide these lists are described above). There are a number of size distributions that can be used: Craters Only, Plain Craters, Halos, Parabolas, and Splotches.

In the Craters Only size distribution, the diameters of just the craters and their ejecta (including ‘fluidized ejecta’ or crater outflows) are used.

Craters with associated parabolas are not included, though craters with halos are included. Craters are treated as circular and the diameter of the continuous ejecta is taken to be twice that of the crater itself. This gives a fairly close approximation for those craters with radially symmetric ejecta blankets; while it is a poor approximation for the shape of asymmetric ejecta blankets, the total area should not be too dissimilar (there are very few significantly noncircular craters, as opposed to noncircular ejecta blankets). The Plain Craters distribution is identical to Craters Only except that craters with associated halos are not included.

The Halos, Parabolas, and Splotches size distributions use the measured diameters or equivalent diameters (in the case of significantly noncircular features).

4.2.2 Feature Size Sequences

At any given time in a simulation, SimVenus draws impact feature sizes from a size distribution file as described above. Over the course of a simulation, however, which size distribution file is being used can change. For example, sizes might be drawn first from Craters Only, then from Parabolas; this is referred to as a feature size sequence. The three feature size sequences that have been used in this work are Craters Only (CO), Extended Ejecta (EE), and Full Sequence (FS).

Craters Only (CO)

In the Craters Only sequence, CratersOnly is the first distribution used, followed by Parabolas. This was the first sequence used, and was used prior to the measurement of halo sizes (i.e., when CratersOnly and Parabolas were the only size distributions available). Since halos are an important constraint, this sequence is not favored. CO sequence results are included in this work primarily to show the constraining effect of halos.

This sequence ignores halos completely; physically, it is equivalent to assuming that any embayment of a halo somehow obliterates the halo completely, so that it is impossible to observe an embayed halo. This is considered highly unlikely.

Extended Ejecta (EE)

In the Extended Ejecta sequence, Plain Craters and Halos are used simultaneously, followed by Parabolas. This sequence was used after the halo diameters had been measured but before SimVenus was improved to keep separate statistics of plain craters and halos. While this does constrain the resurfacing history, it may constrain it too much by putting halos too far back in the past.

Physically, this sequence is equivalent to assuming that halos have a natural lifetime longer than the simulation, and are only removed by resurfacing. In this view, the reason not all craters have halos is that some combination of impactor velocity, composition and incident angle is required to form a halo.

Full Sequence (FS)

When the Full Sequence is used, Plain Craters are emplaced first, followed by Halos, followed by Parabolas. SimVenus was only recently modified to allow separate record-keeping for different classes of features, making this sequence possible. This is felt to be the most likely of the sequences.

Physically, this is equivalent to assuming that all craters form parabolas and halos, but that parabolas degrade quickly and that halos degrade somewhat more slowly. Since no provision is made for different lifetimes for different crater sizes (or the probability that very small craters are unable to form parabolas), it is still imperfect. A better understanding of these features is required to correct these problems.

4.3 Resurfacing Event Emplacement

Resurfacing events are emplaced at varying intervals. For any given run of SimVenus, a time model is specified. Possible models are fixed rate, linearly changing rate, and exponentially changing rate. A model whereby the rate changes linearly at first then changes to a fixed rate is also available; this is referred to as the modified linear model. Testing of the ER model used the constant rate time model, while tests of the GR model used all of the time models; the models are discussed more thoroughly in the Equilibrium Resurfacing and Global Resurfacing sections.

When an event is emplaced, a location is determined randomly. The method is as described for crater emplacement, above. A size for the event is chosen from a list of volcanic feature sizes.

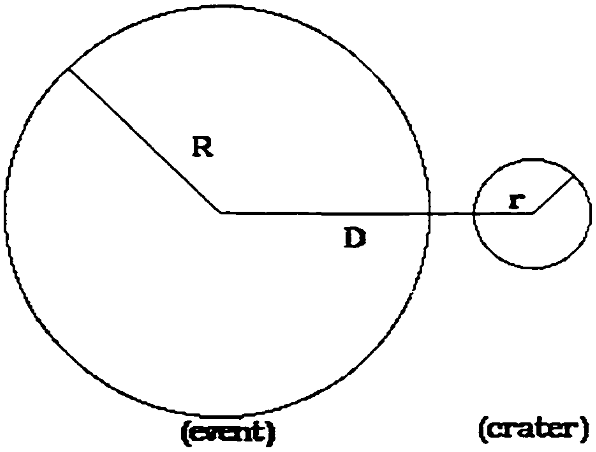
4.3.1 Effect On Impact Features

When a resurfacing event is emplaced, each crater is checked to see if it will be affected by the event. If the event and crater do not overlap (distance between crater and event larger than sum of crater radius and event radius), the crater is unaffected. If the event completely covers the crater (radius of event larger than distance to crater plus crater radius), the crater is considered to be destroyed. If the event overlaps the crater partially but not completely (all other cases), the crater is considered embayed. Figure 9 shows the possible cases.

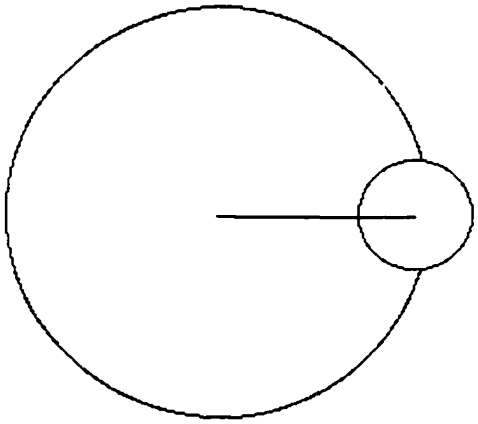
As noted in Chapter 1, the decision to model only two dimensions means that no attempt was made to estimate the crater rim heights or lava flow thicknesses. The radius of a resurfacing event in this model must be interpreted as 'the radius at which the thickness is sufficient to completely cover any crater.' It is likely that the flow would extend some distance beyond this, embaying but not destroying any craters it encountered. This would tend to elevate the number of embayed craters; conversely to keep the same number of embayed craters, this requires us to lower the resurfacing rate. This uncertainty means that resurfacing rates produced by this program must be regarded as upper limits.

"Heavily Embayed" Craters

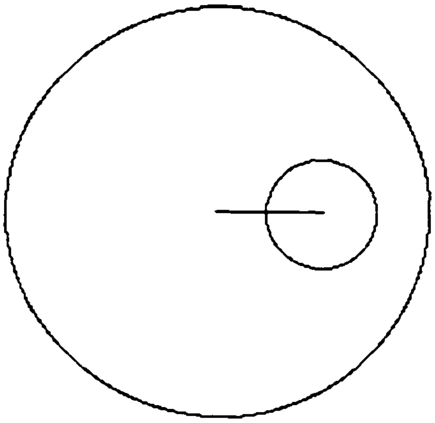
Another aspect of this problem is that it is difficult to decide exactly when embayment will completely destroy a crater. As noted above, SimVenus assumes that if a single resurfacing event completely covers a crater, it is destroyed, while a partial covering results in embayment.



1) D > R + r (crater is unaffected)



2) R-r < D < R+r (crater is embayed)



3) D < R-r (crater is destroyed)

Figure 3 : Possible Fates Of A Crater In SimVenus

Figure 9. Possible fates of a crater in SimVenus. In the three drawings above, the smaller circle represents the crater (with radius r). The larger circle represents the resurfacing event (with radius R). D is the distance between their centers (the length of the straight line).

If a single crater is repeatedly embayed without ever being completely covered by a single event, it seems reasonable that it might be obliterated. The scarcity of embayed but still recognizable craters on Venus may suggest either that embayment easily removes them or, alternately, that the issue does not arise because few craters are actually embayed. SimVenus tries to address this problem by having a "heavily embayed" category of features.

Two endmembers can be identified. At one extreme, no number of partial embayments will ever remove an impact feature; at the other extreme, two partial embayments of any degree suffice to destroy an impact feature. In this work, these are referred to as the DME=0 and DME=1 assumptions, respectively, after the probabilistic analysis of the ER model, presented in Appendix A. Neither of these endmembers is particularly realistic, but the true effect should lie between them, so all runs were done under both assumptions to provide bounds.

SimVenus is written to run with either endmember or an intermediate model that was used in the early work (published in *Schaber et al.* [1992] and *Strom et al.*, [1994]). In the intermediate model, whenever an event partially embays a crater, the percentage of the crater covered is calculated and recorded. When an event covers the center of a crater, this fact is also recorded. If the cumulative percentage of the crater embayed is more than 100 percent and its center has been covered at some point, the crater is considered heavily embayed and probably destroyed. In general, the number of such craters is quite small. Historically, this was the first option available; the endmembers were added as options to allow the entire range of possibilities to be determined.

4.4 Time Domains

As discussed above in Section 4.2.2, impact feature sizes are drawn from different size distribution files at different times in the simulation. This is accomplished by defining time domains in which the feature sizes are specified. For example, SimVenus might be instructed to use one feature size distribution for the first hundred million years, then use a different one for the next hundred million years and so on. Records are kept for each time domain individually as well as for the simulation as a whole. It is also possible to specify resurfacing rates for different time domains (see the Compound Constant Rate model in chapter 5, for example), or to have the program enter a new domain (for purposes of record-keeping) based on a defined criterion.

An example of changing record-keeping based on domain is in the Exponential model: when the End-Of-Dieoff Criterion is met, a new time domain is begun. While the resurfacing rate and feature sizes remain the same, this allows the program to distinguish between embayments which occur during the tail end of the GRE and those which occur afterward (see the Exponential Decay model in chapter 5 for more on this).

Output Modes

SimVenus has two output modes. In individual run mode, a simulation is run once, and the output is printed to a file. Included is a listing of all impact features, with their location, radius, embayment status, and time of emplacement. In statistical mode, some number of simulations (for this work, 50, unless otherwise stated) are run. The individual impact feature information is not included, but the other results have the output averaged over all the runs. The average output is then printed to a file.

CHAPTER 5

MODELLING EQUILIBRIUM RESURFACING

The equilibrium resurfacing (ER) model was first proposed by *Phillips et al.* [1992] to explain the cratering record of Venus. Along with the global resurfacing (GR) model, it was one of the two main contenders for a resurfacing history of Venus. In *Phillips et al.*[1992], both a probabilistic analysis and Monte Carlo simulations of the ER model were presented: SimVenus was originally written to test these results. Largely as a result of the work done with SimVenus, the ER model has been abandoned. While the ER model is not currently considered a viable theory, it is an important part of the history of this work and hence is included here.

5.1 The Equilibrium Resurfacing Model

The equilibrium resurfacing model takes as its premise that the number of craters on Venus is in equilibrium, with craters being destroyed by volcanism at the same rate as they are produced. In the general form of the model, it is not specified for how long the population has been stable.

The current known cratering record contains nearly 1000 craters. For this population to be in equilibrium, approximately 0.1 percent of the

Venus surface must be resurfaced during each cratering interval, on average. This can be accomplished through large resurfacing events occurring infrequently, or small events occurring frequently, or through some combination of large and small events.

As the large but infrequent endmember of the spectrum is approached, it becomes questionable whether it can still be called 'equilibrium' resurfacing. In the extreme of a single, whole-planet event occurring every 1000 cratering intervals or so, it is equivalent to the global resurfacing model.

Appendix A contains a probability analysis of the ER model, done independently of the analysis by *Phillips et al.* [1992], and using a slightly different approach. This analysis gives the same results as those of *Phillips et al.* [1992]. SimVenus runs made to duplicate the conditions described in the analysis (e.g., single-size resurfacing events and craters) agreed with the predictions of this analysis.

5.2 Applying The Criteria To The ER Model

Upon first consideration, the ER model seems a good candidate for the resurfacing history of Venus. It certainly meets the criterion of low crater count: by adjusting the resurfacing rate, the equilibrium count can be easily adjusted. Random crater emplacement and random erasure should combine to meet the random distribution criterion, at least over length scales comparable to resurfacing event size (suggesting that the small and frequent endmember will be suitable, though the large and infrequent endmember will not). The question of low embayment rate is not as easily answered, however, leading to this work.

More careful consideration reveals a problem. Conceptually, it can be seen that the extended criteria put additional limits on the ER model. The constraint imposed by the parabolic criterion is that resurfacing during the last 25 million years or so must have been low enough to avoid embaying any of the parabolas; the halo and splotch criteria are similar but for longer time periods. This suggests that the small and frequent resurfacing endmember is unsuitable, but does not affect the large and infrequent endmember. Combined with the conclusion above, that large and infrequent events are unsuitable because they will not produce a random distribution of craters, this implies that it may be very difficult to make the ER model work.

5.3 Results of Phillips et al.

In their 1992 paper, *Phillips et al.* state that they performed numerical simulations at a variety of points along the spectrum from large/infrequent to small/frequent. According to them, they matched the observed random distribution in two domains: resurfacing areas greater than about 10% of the surface and areas smaller than about 0.03% of the surface. They did not model embayment; craters were treated as points, which were either destroyed or unaffected by resurfacing events. However, they did a probabilistic analysis of embayment and stated that the low embayment criterion was met as well.

SimVenus was originally written to test these results. Achieving random distribution with resurfacing areas greater than 10% of the surface was considered highly suspect. While plots showing the random distribution of craters in the 0.03% case were included, no such plots were included from the 10% cases. The simplifications involved in the probabilistic analysis were also a cause for concern.

5.4 SimVenus Results

The results of SimVenus disagreed strongly with the results of *Phillips et al.*[1992], giving highly non-uniform spatial distributions for resurfacing areas greater than 10% of the planet; the results of a typical run are shown in Figure 10. While resurfacing areas smaller than 0.03% of the planet did give uniform spatial distribution, they also resulted in very high fractions of embayed craters.

More specifically: SimVenus was run with total durations ranging from 2 billion to 5 billion years, with events equal to .03% Venus surface in size, crater interval of 400,000 years, and resurfacing interval of 100,000 years. While these runs did yield approximately the correct number of total craters, they produced approximately 330 embayed craters, over six times the observed number. Runs with even smaller, more frequent resurfacing events gave even more embayed craters.

These disagreements were first cited in *Schaber et al.* [1992]. The exact reasons for this disagreement are unknown. While some workers have since proposed lower total crater counts and higher embayment rates, none of the alternate totals have even approached the level of embayment reported above.

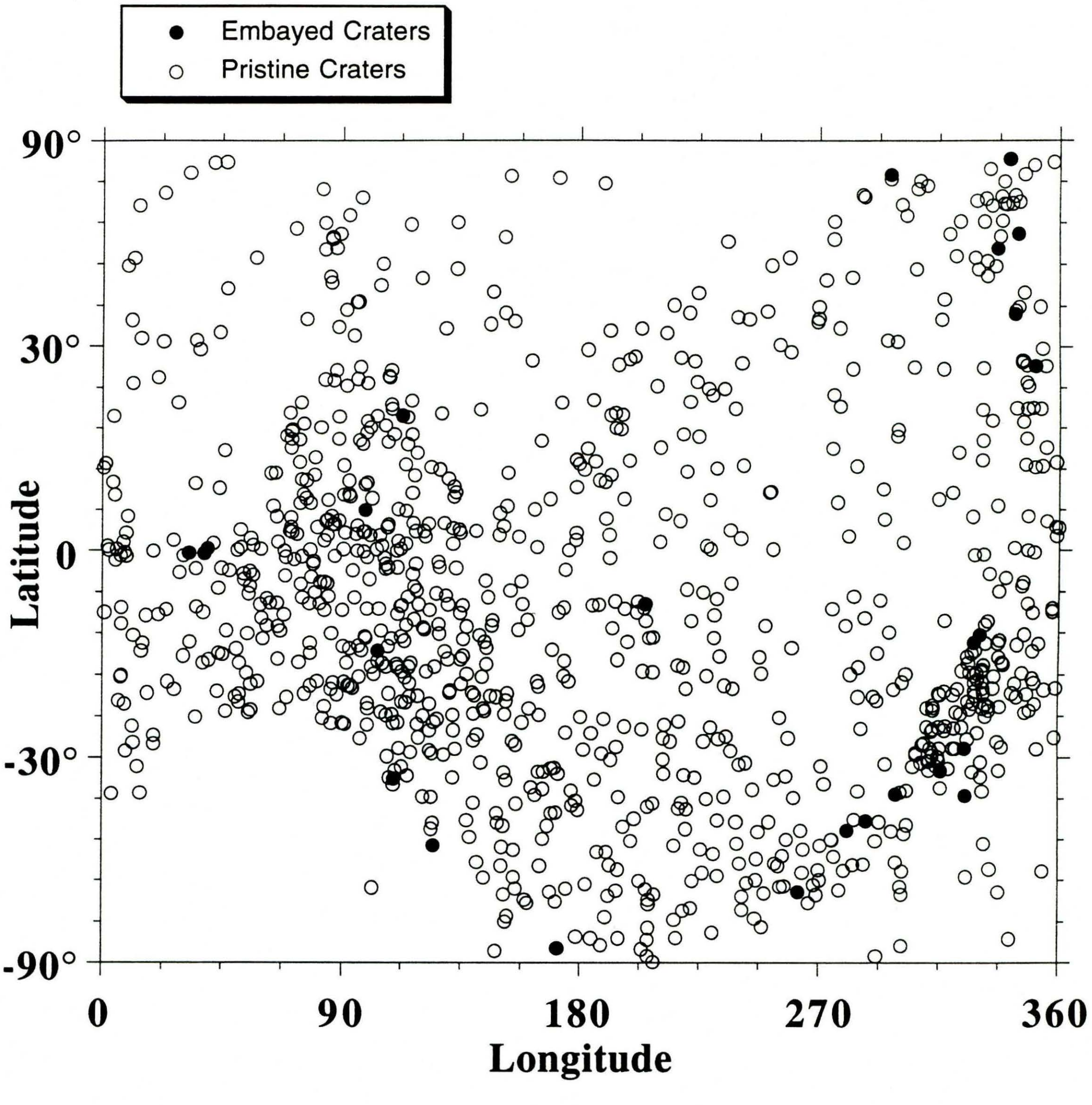


Figure 10. Results of a typical ER run of SimVenus. For this run, resurfacing patches equal to 10% of the planetary surface were used.

5.5 Other Arguments

Additional arguments against the ER model, not addressed by SimVenus, include that it requires volcanic resurfacing to be randomly distributed across the planet while it seems much more physically likely that at least recent activity would be localized. While SimVenus models resurfacing for the GR model randomly, it is far from required by the model.

This becomes especially problematic when the evidence of Figure 3 (Section 3.2) is taken into account. The more recent embayments are highly concentrated into one region. It is a serious asymmetry to a model which predicts complete symmetry. It suggests that most of the recent resurfacing has been taking place in that region; if the level of resurfacing is high enough to be keeping the population in equilibrium, then there should be a clear deficit of craters in that region, which there is not.

Also, since large craters would be expected to be more resistant to destruction than small ones, the ER model would predict a steepening of the size distribution function. The observed distribution function is consistent with expected atmospheric effects and does not seem to have been steepened further beyond that, though this is an area that does not seem to have received much attention.

5.6 ER Conclusions

SimVenus runs show that using the ER model with relatively large and infrequent resurfacing yields a distinctly nonuniform spatial distribution of craters. The early results of *Phillips et al.* [1992] which claim, in contradiction to this, that it can produce a uniform distribution have never been duplicated nor referred to again by the authors and can probably be regarded as in error.

SimVenus runs show that using the ER model with relatively small and frequent resurfacing produces far too many embayed craters. This is found despite SimVenus agreeing with the lower embayment rates predicted for a single-size cratering population and single-size resurfacing event population, as assumed in the probablistic analysis of both *Phillips et al.* [1992] and Appendix A of this work.

Due to the failure of large/infrequent events to produce a uniform spatial distribution of craters and the failure of small/frequent events to produce an accurate count of embayed craters, the equilibrium resurfacing model is rejected as an explanation for the Venus cratering record.

CHAPTER 6

MODELLING GLOBAL RESURFACING

The premise of the global resurfacing (or GR) model is that at some point in the past, all (or very nearly all) of Venus was resurfaced within a fairly short time (for an event of this scale). Following the cessation of this global resurfacing event (or GRE), resurfacing dropped to a comparatively tiny rate. The surface was nearly a blank slate when the GRE ended and has only undergone minimal resurfacing since that time.

Before, During And After The Global Resurfacing Event

The GR model does not make any assumptions or put any constraints on the history of Venus prior to the GRE. In fact, it produces the result that to the extent to which the GRE is truly global, that prior history is unknowable (though sufficiently small older regions might survive). Similarly, the GR model has nothing to say about the history of Venus during most of the GRE: the GRE could be near instantaneous on a geological time scale or persist for hundreds of millions of years; in the latter case, the term "event" is insufficient to describe it (global resurfacing period seems more appropriate), but will be used regardless.

The earliest time in which the GR model can be used to provide information is the transition from the GRE to the minimal resurfacing later. This period will be referred to as the tail-end or dying-off of the GRE. The period of later, reduced resurfacing will be referred to as the post-GRE period.

6.1 Applying The Criteria To The GR Model

The GR model predicts that the cratering record of Venus should be essentially a production population, after atmospheric screening, with all craters randomly located. Thus, it easily meets the random distribution criterion. The low total count criterion is met by specifying that the GRE occurred relatively recently (not much more than 950 cratering intervals in the past). The low post-GRE resurfacing seems likely to meet the low embayment criterion, but in order to test this, the nature of the post-GRE resurfacing must be specified. As will be seen, it is not difficult to create a post-GRE history which succeeds in this, but meeting the extended criteria at the same time proves to be problematic.

6.2 SimVenus Results

SimVenus was used to test the implications of the GR model. To encompass the range of possibilities, all runs were made using the two extreme assumptions of multiple embayment (see Section 4.3.1): 1) that no amount of multiple embayment could destroy a crater (the DME=0 case); and 2) that double embayment was sufficient to destroy a crater (the DME=1 case). All results were achieved by averaging 50 runs.

Initially, all runs were made using the Craters Only sequence of sizes (see section 4.2.2 for a description), as this was the only sequence available. Later, after measurements of halo diameters were made, the Extended Ejecta sequence was used. Later still, after SimVenus was improved, the Full Sequence was developed. The Full Sequence runs are the best model of the impact history of Venus and are presented below. For purposes of comparison, the Craters Only and Extended Ejecta results are included in Chapter 7.

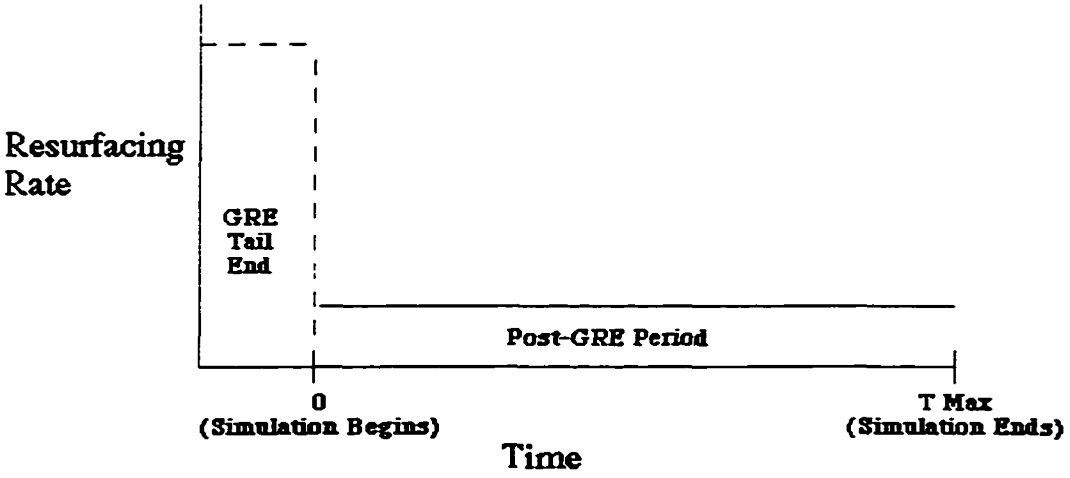
Tail-End of GRE versus Post-GRE Periods

As discussed at the beginning of this chapter, a distinction can be drawn between the period during which the GRE is still ending and the period in which it is completely finished. While this distinction may prove to be somewhat arbitrary near the transition, it is still a useful one, especially if we wish to use the stratigraphic criterion. For this reason, SimVenus keeps track of how many craters were embayed during each period separately.

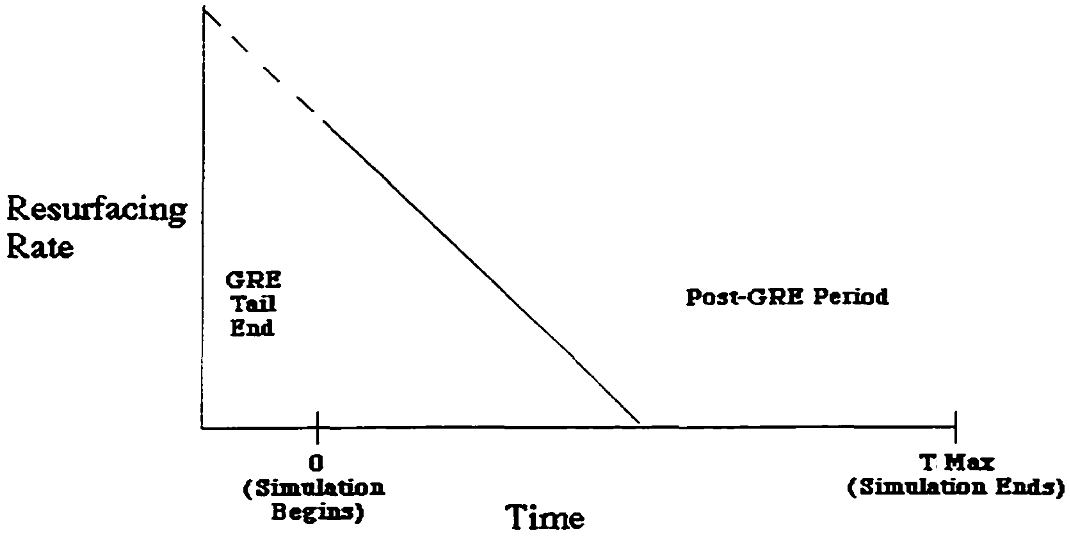
Two facts are primarily sought by making this division: how long does it take for the GRE to end, and what portion of the planet has been resurfaced since it did? The former number may be able to constrain efforts to model the GRE itself, while the latter provides a general measure of the level of activity of the planet.

6.3 Time Models

In the general GR model described above, no form was specified for the time-dependence of the resurfacing rate in either the tail-end of the GRE or the post-GRE period. In order to constrain the recent geologic history of Venus more precisely, it is necessary to specify the resurfacing rate more precisely. As discussed in section 4.1, SimVenus is designed to use a number of different time models: constant, linear, and exponential, as well as combinations of some of these. Each of these time models has application in the GR model and has been tested for suitability; each is described in detail below. Figures 11-13 show the resurfacing rate as a function of time for each model.

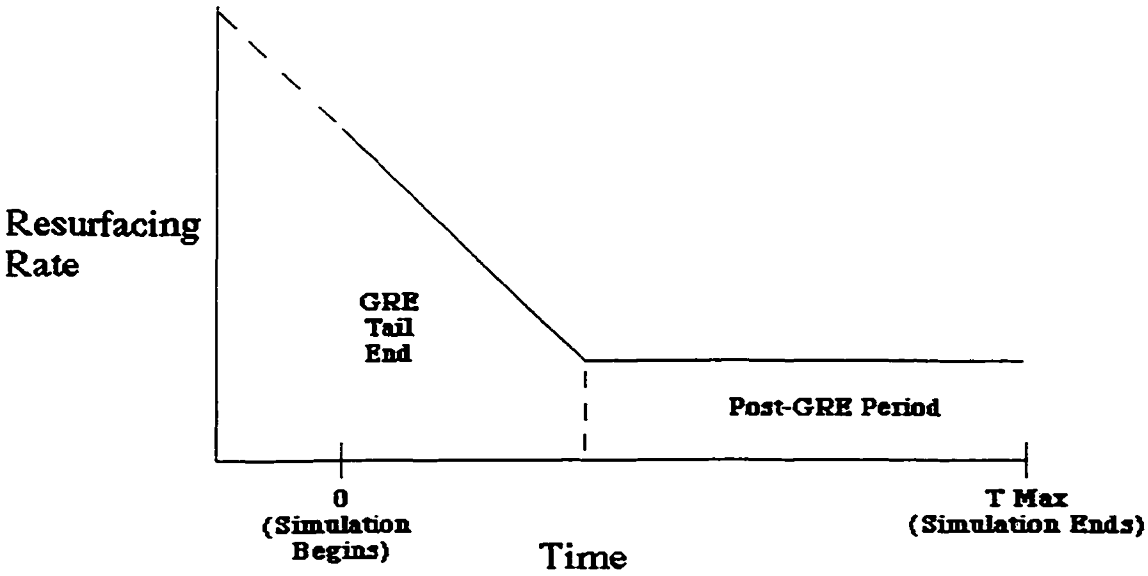


Case 1 : The Instant Cutoff Model

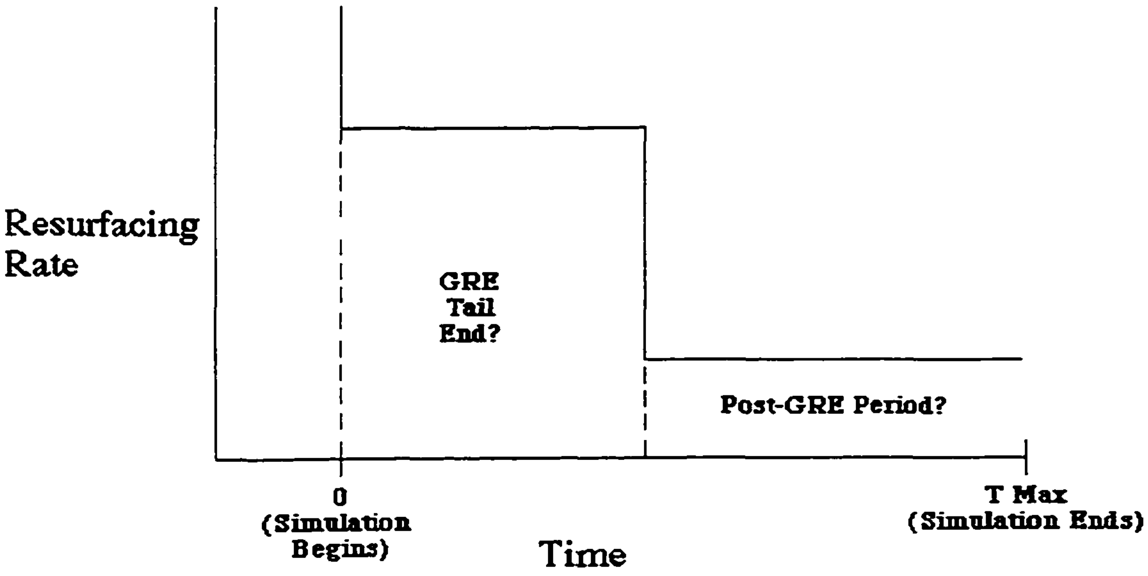


Case 2 : The Linear Decay Model

Figure 11. The constant and linear time models for SimVenus.

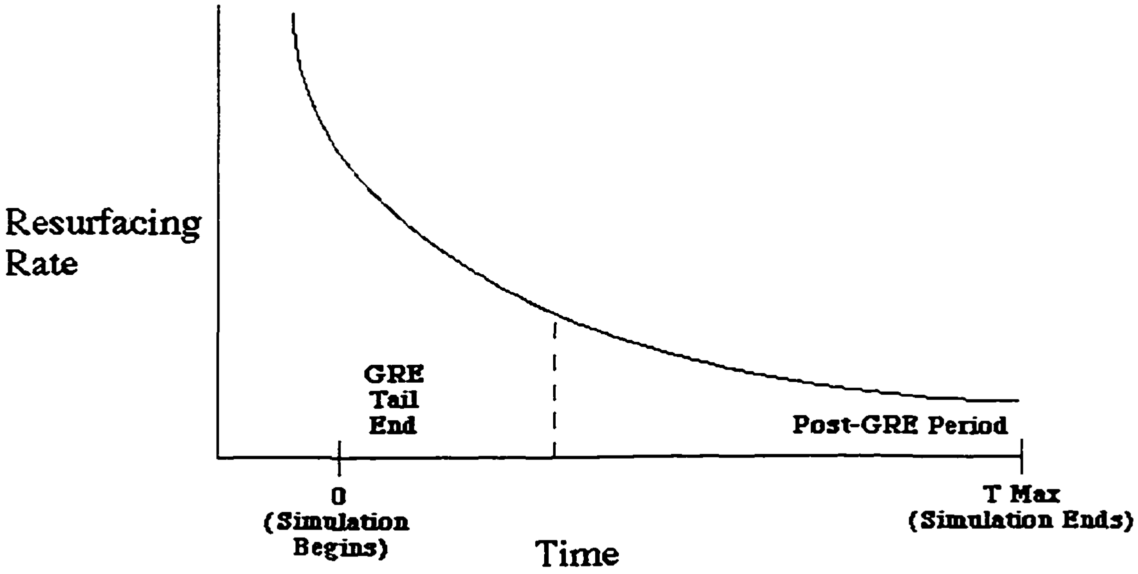


Case 3 : The Modified Linear Model



Case 4 : The Compound Constant Model (Two Periods)

Figure 12. The modified linear and compound constant time models for SimVenus.



Case 5 : The Exponential Decay Model

Figure 13. The exponential time model for SimVenus.

6.3.1 Constant Resurfacing Rate

The simplest time model is a constant resurfacing rate: an interval between resurfacing events is specified and remains constant for the length of the simulation. In simulating the GR model, it represents an instantaneous end to the GRE: the simulation switches instantly from a completely resurfaced planet to the low level of post-GRE resurfacing. All embayment in this case is due to post-GRE resurfacing.

It proved possible to adjust the input parameters to satisfy the basic criteria without much difficulty. However, the resurfacing rate needed to produce 50 embayed craters was too high to avoid embaying halos and parabolas, so the extended criteria were not met.

When the DME=0 assumption (multiple embayment never results in crater destruction) was used, the necessary resurfacing interval was 270,270 years. 16.0% of the planet was resurfaced during the simulation. The total duration of the simulation was 3.987 x 10^8 years. 3.9 parabolas and 10.64 halos were embayed.

When the DME=1 assumption (double embayment is sufficient to destroy a crater) was used, the necessary resurfacing interval was 255,000 years. 16.9% of the planet was resurfaced during the 4.012 x 10^8 years of the simulation. 3.84 parabolas and 10.82 halos were embayed.

While the results for the DME=0 and DME=1 runs are rather similar in this case, they do show patterns that will recur under other time models. Because embayed craters are removed more easily under the DME=1 assumption, the resurfacing rate must be increased to compensate. This results in larger fractions of the planet being resurfaced and more parabolas and halos being embayed. It also results in more craters being destroyed, which requires an extension of the simulation duration to replace the extra destroyed craters.

Using the basic criteria alone, the constant rate model was viewed as acceptable, although physically unlikely, since it implies an instant transition from extremely high resurfacing rates to very low ones. Because it provides no tail-end of the GRE, it is impossible to apply the stratigraphic criterion to the constant rate model. Taking the extended criteria into account, however, it is clearly unsatisfactory.

6.3.2 Linear Decay Of Resurfacing Rate

The linear decay model of the resurfacing rate is defined as follows:

$$R(T) = R_i - (R_i - R_f)*T/T_{RUN}$$

In the linear model, the resurfacing rate, R, decays linearly with time (T) from an initial rate (R_i) to a current-day value, or to zero at some point in the past. If R_f is positive, it represents the current-day resurfacing rate. If it is negative, it is related to how long ago the resurfacing rate dropped to zero, but has no meaning in itself. In the GR model, this represents a GRE which ends slowly, gradually fading away. Under this model, either the GRE is still fading away in the present or the post-GRE resurfacing rate is zero. In either case, all of the observed embayment is due to the tail-end of the GRE.

Because this model explicitly tries to begin with the GRE still in full force, it was necessary to start with a resurfacing rate high enough to model the GRE. It was decided that if the entire planet were resurfaced in, on average, 1 million years, this would suffice. The average resurfacing event size is roughly 0.01% of the planetary average, so this required 10,000 events in 1 million years, or a resurfacing interval of 100 years.

Using this as an initial resurfacing rate, it proved not to be possible to meet the criteria. More specifically, this model always produced too few embayed craters. Even pushing the beginning of the simulation back to 4e9 years in the past, not enough craters ended embayed; while many craters were transiently embayed, nearly all were subsequently destroyed. The decrease of resurfacing with time apparently occurred too slowly.

Recognition of this problem led to the creation of the modified linear time model.

6.3.3 Modified Linear Decay Of Resurfacing Rate

The resurfacing rate in the modified linear model is defined as follows:

$$(\text{For } T<T_1) \quad R(T) = R_i - (R_i - R_f)*T/T_1$$

$$(\text{For } T>T_1) \quad R(T) = R_f$$

In the modified linear model, the resurfacing rate decays linearly from an initial rate (R_i) to a specified final rate (R_f) at a specified time (T_1); when the specified time is reached, the resurfacing rate becomes constant. In the GR model, this represents a GRE ending slowly but with "background" non-GRE resurfacing going on. Under this model, embayment that happens before the switch to a constant rate is considered due to the tail-end of the GRE while embayment that happens afterward is considered due to post-GRE resurfacing. The clear distinction between the two is a primary advantage of this model.

Being a combination of the linear and constant rate models, the modified linear model proved to share both of their shortcomings. While it did prove possible to meet the basic three criteria, it was only possible for small numbers of craters embayed during the tail end of the GRE. In these cases, not only was the parabolic criterion violated, albeit to a slightly smaller degree than in the pure constant model, but the idea of the global resurfacing model was pushed beyond recognizability: the resurfacing rate 'tailed off' over a period approaching three billion years.

6.3.4 Exponential Decay Of Resurfacing Rate

The exponential decay model of the time dependence of the resurfacing rate is defined as follows:

$$R\ (T) = R_f + (R_i-R_f)*\exp\ (-T/\tau)$$

In the exponential model, the resurfacing rate (R) decays exponentially from a specified initial rate (R_i) towards a specified "final" rate (R_f), with a specified decay constant (τ). In the GR model this represents a fading GRE with ongoing "background" resurfacing. In many ways, this is simply a more continuous, and arguably more physically reasonable, version of the modified linear model. Of the resurfacing rate models developed in this work, the exponential decay model is probably the best approximation for representing those internal models which have a catastrophic crustal foundering of overturn followed by slow thickening of the crust.

The primary difficulty with using the exponential model is that there is no significant distinction between the dying-off of the GRE and the post-GRE period. Indeed, the primary attraction of the exponential model is that it describes a continuous process. Thus, we cannot apply the stratigraphic criterion in the same way as we apply it to the modified linear model or compound constant rate model: that is, we cannot produce runs with varying numbers of embayments ascribed to the 'tail-end of the GRE' versus numbers of embayments ascribed to the 'post-GRE period.'

This realization came quite late in this work; a substantial amount of work, including *Strom et al.* (1994) was done attempting to force the exponential model to use the same procedure as the other models, involving creating a rather arbitrary criterion for marking the end of the 'tail-end of the GRE.' While this approach was finally discarded, it is discussed more fully in Appendix B.

Results

For the exponential case, as with the modified linear and the compound constant case, it proved possible to achieve basic criteria with a range of input parameters, and so a number of runs were done over that range.

However, once the extended criteria were applied, only one run, with DME=0 and a slow decay, was still found acceptable.

As noted earlier in this section, applying the stratigraphic criterion is problematic, since there are no clear-cut distinctions between different periods. To address this issue, SimVenus was modified to produce a list of how long it took to embay increasing numbers of craters (producing the last time a given number of embayed craters was reached) as well as the area which has been resurfaced at those times. Figure 14 shows the average length of time it took to embay various numbers of craters (averaged only over the runs which actually produced that number of embayed craters; for example, since only one run produced 64 embayed craters, the value for 64 craters is how long it took that single run to embay 64 craters).

If we look at Figure 14 with the stratigraphic criterion (13-18 craters embayed by the emplacement of the plains) in mind, then it is implied that the plains emplacement lasted on the order of 95-110 million years. Using the amount of resurfacing done at those times, it can be derived that after the end of plains emplacement, a further 133-228% of the planet was resurfaced.

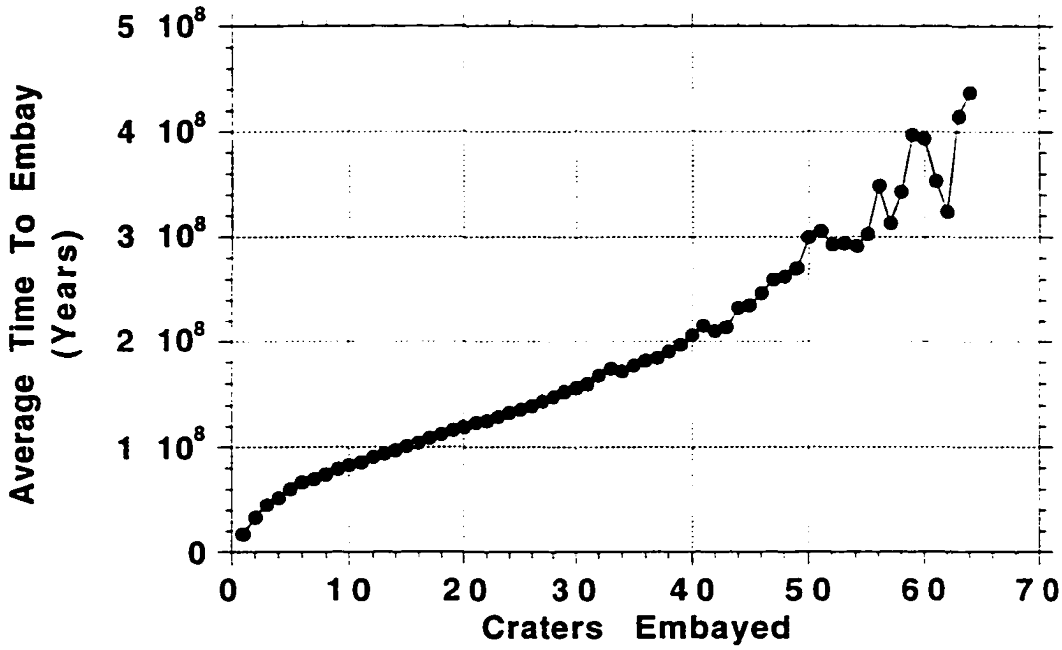


Figure 14. Craters embayed versus time.

Time required to embay varying numbers of craters, using the exponential model with the DME=0 (multiple embayments never destroy a crater) assumption. Because the constraint that 50 craters be embayed was only applied to the average of a set of runs, individual runs could have more or less than that number, which is why the above figure extends to 64 craters embayed.

The exponential model, then, satisfies the basic criteria easily, with a variety of parameters possible. The extended criteria restrict this range to the slower-decaying extreme. Applying the stratigraphic criterion requires a different interpretation than other models, but suggests a duration for the plains emplacement (possibly the last major event of the GRE) of 95-110 million years. However, there is still a great deal of resurfacing (over 100% of the planetary area) after this time, which violates part of the stratigraphic criterion.

6.3.5 Compound Constant Rate

The resurfacing rate in the compound constant rate model is defined as follows:

$$(\text{For } T<T_1) \quad R = R_0$$

$$(\text{For } T_{i-1}<T<T_i) \quad R = R_i \qquad (I=1,\ n)$$

where R is the resurfacing rate, T is time, R_i is a set of constants, and T_i is the end of the ith time period.

In the compound constant rate model, the resurfacing rate is assumed to drop very quickly (instantly, in SimVenus) from the GRE to a much lower rate, which is constant for some length of time. Then at some later point, the rate drops very quickly again to a new rate, which in turn remains constant. This is repeated for any desired number of periods.

This model was created due to the fact that none of the other models were able to satisfy all the criteria, usually failing the extended criteria (although see the exponential model, below). While a very clear distinction may be drawn between the different periods, this distinction is of dubious value, since even the initial period does not correspond very well to the tail end of the GRE. It may nevertheless be possible to identify the first period as responsible for most of the plains emplacement, as described in *Collins et al.* [1997].

Initially, for the Craters Only sequence, only two time periods were used. The first time period, with a higher resurfacing rate, represents the end of the GRE. The second time period, with a lower resurfacing rate, represents the post-GRE period. In order to meet the parabolic criterion, the highest resurfacing rate during the second time period was forced to be so low that it was not possible to embay as many as 2 craters in the post-GRE period, a result at odds with the stratigraphic criterion. These results are discussed in more detail in chapter 7; no 2-period compound constant model runs were made with the Full Sequence of size distribution files.

Using three time periods made it possible to satisfy both the basic and extended criteria while the durations and resurfacing rates of the first two periods could be varied to achieve varying proportions of embayments. The results are shown in Table 3. Figure 16 shows how the duration of the tail end of the GRE varies with the number of craters embayed during that period. Figure 17 shows how the fraction of the planet resurfaced after the GRE varies with the number of craters embayed during the tail end of the GRE.

To apply the stratigraphic criterion, we may use the *Collins et al.* [1997] figure of some 13 to 18 embayments being due to the ending of the GRE and associate this with the first time period of this model. If we do so, then we get a duration of something like 95(±25) million years for the emplacement of the plains/tail end of the GRE. For post-GRE resurfacing, we get a range of approximately 15-22% of the surface.

All the criteria are met, then, for a three-period compound constant rate model. The basic and extended criteria are met, as can be seen in the detailed results of the runs in Appendix E (as runs CL0-CL5 and runs CM0-CM5). Also, the ability to vary the proportions of embayed craters between the first and later time periods allows us to try to apply the

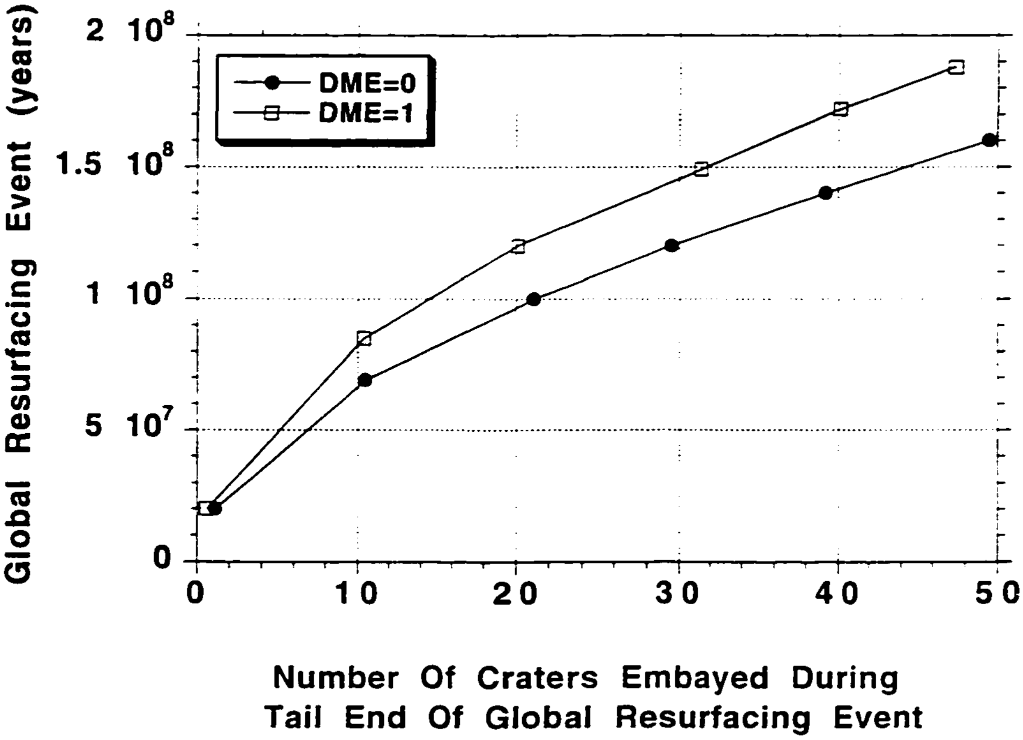


Figure 15. GRE compound constant results (T1). Variation of GRE Tail-End Duration with number of craters embayed then, for a three period compound constant rate time model.

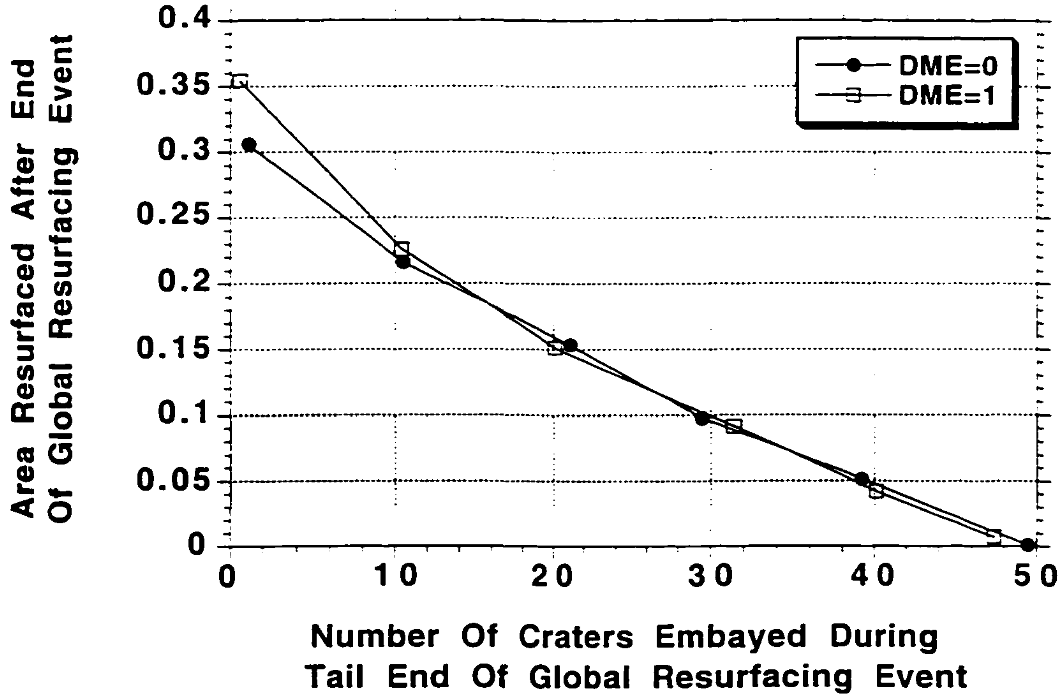


Figure 16: Variation of area resurfaced after GRE with number of craters embayed during end of GRE, for a three period compound constant rate model.

stratigraphic criterion. The three-period compound constant rate model is found to be the most satisfactory of the GR models.

6.4 Inclusion Of Splotches

Including splotches in SimVenus was problematic, because of the unanswered questions about their distribution, production rate, and lifetime (see section 3.3.3 for more details). As a result, instead of routinely including them in all runs (or creating a size sequence including them, and then using that sequence), a few selected sets of parameters were chosen, and splotches added to those runs.

Approximately 400 splotches have been identified and measured, so in all of the runs described in this section, 400 splotches were emplaced. There may very well be far more splotches, but these are the only ones we can be sure are not embayed, and at least gives us an idea of the effect of including them. Because splotches are believed to be formed by a similar mechanism to that of halos, it was assumed that they would have a lifetime similar to that of halos (possibly somewhat shorter, since they may have been formed by smaller and weaker impactors). With a cratering interval of 400,000 years and the simplifying assumption that all craters form halos, halos have a lifetime of approximately 1.5×10^8 years. For most of the runs described below, a splotch lifetime of approximately 10^8 years was used, with this number being varied in some runs to see how this would affect the results. Table 10 summarizes the results of these runs; all runs satisfied the three basic criteria.

As can be seen from Table 10, the constant rate and exponential rate models, while passing the three basic criteria, fail all three extended criteria. The compound constant rate model succeeded in passing the splotch criterion just as it did the parabola and halo criteria, without any further modification of the input parameters. In other words, including the splotches had no effect on the applicability of any of the models.

Increasing the splotch lifetime to 1.5×10^8 years, roughly the same as the estimated halo lifetime if all craters form halos, led to a borderline failure of the splotch criterion. Increasing the splotch lifetime to 2.0×10^8 years led to a definite failure of the splotch criterion. These results suggest that the intuitive idea that the splotches have a lifetime which is similar to, or shorter than, that of halos, is reasonable.

Time Model	DME	$T_{splotch}$	E_P	E_H	E_S
Constant	0	1e8	3.32	11.22	15.68
Constant	1	1e8	3.52	10.84	14.60
Exponential	0	1e8	2.52	6.92	9.44
Exponential	1	1e8	2.20	7.00	9.90
CCR	0	1e8	0.04	0.40	0.46
CCR	0	2e8	0.00	0.40	5.20
CCR	0	1.5e8	0.00	0.40	0.8
CCR	1	1e8	0.02	0.20	0.46

Table 2: SimVenus Splotch Results.

400 splotches were used in these runs.

'Time Model' indicates which model was used for the time-dependence of the resurfacing rate, as described in the first sections of this chapter.

'DME' indicates what multiple embayment assumption was used (DME=0: multiple embayment never destroys a crater; DME=1: double embayment destroys a crater)

$T_{splotch}$ is the lifetime of splotches used, if not destroyed by resurfacing events.

E_P, E_H, and E_S are the numbers of embayed parabolas, halos, and splotches, respectively.

6.5 Estimates Of Magmatic Flux

It is possible to use the results of the various GR model runs described above to produce estimates of the magmatic flux on Venus, by assuming a depth of lava produced in a resurfacing event and multiplying this by the total area resurfaced. This was done in *Strom et al.* [1994], producing estimates of only 0.01 - 0.15 km^3 per year, by assuming a flow thickness of 1 km. This amount is comparable to magmatic production at Hawaii.

McGovern and Solomon [1996] model the volcanic structure likely to occur on Venus and conclude that moats several kilometers deep would form. This would tend to minimize the area covered (and hence the number of craters affected) while maximizing the volume of lava produced. This alone could increase estimates of magmatic flux by up to an order of magnitude.

Also, many of the time models described above have higher resurfaced areas than the model described in *Strom et al.* [1994], but results should be proportional.

6.6 Conclusions

The basic premise of the general GR model—that the surface of Venus was wiped clean and that the current cratering record is largely a production surface, only minimally affected by subsequent resurfacing—is clearly compatible with the criteria described earlier. Attempts to refine this general model by specifying the temporal dependence of the resurfacing rate have met with only partial success, however.

Attempts to use simple functions, such as constant, linear, or exponential dependences, fail to meet all the criteria, or in the case of the slow-decay exponential runs, discussed earlier, fail to agree with the stratigraphic evidence of *Collins et al.* [1997]. The only function that has been found to satisfy all the criteria and the stratigraphic evidence is more arbitrary, the compound-constant rate model.

This model is unsatisfying in that it does not give us any additional constraints on the resurfacing history that were not previously known. The arbitrariness of the model is also unsatisfactory, in that other, arbitrarily complex models can almost certainly be proposed that will also meet all criteria. However, it does at least show that the GR model can successfully reproduce the cratering record of Venus in a way that the ER model cannot. Thus, the general GR model is found to be acceptable, with the caveat that it may not be possible at this time to make it more specific.

CHAPTER 7

CONCLUSIONS

This work, and the earlier published versions of these results, allows a number of conclusions to be reached. The simulation process produces reasonable results. The equilibrium resurfacing model produces many problems and is rejected. The global resurfacing model works in general, and we can examine the specific versions of it, rejecting some but finding others acceptable.

7.1 The Simulation Process

The decision to approach this problem by means of a Monte Carlo simulation seems a valid one, allowing as it did rapid implementation of changes in the cratering record database and new time models. Despite the controversy that has surrounded this issue, no analytic approach has been used for anything beyond the ER model.

Similarly, the decision to use a simple two-dimensional model instead of a three-dimensional model seems to have been an acceptable one. While there have been attempts to produce three-dimensional models, their results have not been different enough to justify their much higher demand on computational power and the additional assumptions which must be made. Making runs using both the DME=0 and DME=1 endmembers covers the possibilities sufficiently. Nevertheless, this does mark one of the areas where future work could be most profitable: detailed three-dimensional simulation could narrow the current range of results.

One important result of this work is the recognition that such modelling, while useful, is insufficient. The range of possible time models makes it impossible to decide how many embayments occurred during the tail end of the GRE without further evidence, as witnessed by the heavy reliance on the results of *Collins et al.* [1997] in this work. Even given this additional evidence, the existence of multiple successful sets of parameters means that while modelling can provide a general description of the resurfacing history, it is not enough to exactly specify it.

7.2 The Equilibrium Resurfacing Model

As noted above, the ER model is found inadequate, as it fails to reproduce the observed cratering record. Depending on the exact choices of parameters used, it either produces a noticeably nonrandom crater distribution or results in far too many embayed craters. This finding is admittedly not new to this work, but it was the first major result of the earlier versions of this work.

7.3 The Global Resurfacing Model

As noted above, the GR model is not sufficiently detailed to actually qualify as a model. As a framework upon which to build a more precise model, however, it serves quite well. A partial fit was found using an exponential model and a good fit was found using a compound constant rate model.

The moderately high, or declining from high to low, resurfacing period lasting on the order of 100 million years seems to be a robust result. The resurfacing following the end of the GRE is a more variable result; it proved possible to simulate the cratering record with either between 10 and 20 percent of the planet resurfaced (agreeing with the current interpretation of the stratigraphic evidence) or with the entire planet resurfaced once or twice.

The compound constant rate model—while providing the best fit of the observed cratering record—is not likely to be an exact description of the resurfacing history of Venus, as it is too simplified. It is more likely that the resurfacing rate declined in a way somewhere between the continuously dropping exponential model and the discrete drops of the compound constant model. The pattern of a generally declining resurfacing rate seems likely to be accurate, however.

7.4 The Resurfacing History Of Venus

Putting all the results together, we reach the following conclusions: 1) the recent volcanic resurfacing rate on Venus must have been very low; 2) in the moderately distant past, the resurfacing rate must have been significantly higher, but not incredibly so; 3) in the more distant past, the resurfacing rate must have been incredibly high. That is, the resurfacing rate has been generally decreasing; it may have been continuously or intermittently dropping, but it has been dropping with time.

During the intermediate resurfacing period, the plains were emplaced over a period of roughly 100 million years. Since that time, most of the activity has been concentrated in one area, probably resurfacing some 10-20 percent of the planet. The amount of lava involved is consistent with hotspot activity on Earth.

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APPENDIX A

AN ANALYTIC APPROACH TO THE EQUILIBRIUM RESURFACING MODEL

Since the equilibrium resurfacing model revolves around, unsurprisingly, the concept of equilibrium, it is feasible to at least begin an analytic examination of it. It should be noted that this analysis was done independently and using a somewhat different technique from the analysis presented in *Phillips et al.* [1992], but yields the same results. It was done here as part of an effort to determine why the analytic results described by *Phillips et al.* [1992] differed from the results generated by SimVenus.

I use the following definitions:

N = number of craters (embayed and pristine)
Ne = number of embayed craters
Np = number of pristine craters
N = Ne + Np
C = cratering rate

Pe = probability that a resurfacing event will embay a crater

Pd = probability that a resurfacing event will destroy a crater

Ep = Expected number of pristine craters a resurfacing event will embay

= Pe * Np

Ee = Expected number of embayed craters a resurfacing event will embay

= Pe * Ne

Dp = Expected number of pristine craters a resurfacing event will destroy

= Pd * Np

De = Expected number of embayed craters a resurfacing event will destroy

= Pd * Ne

DME = Destruction through Multiple Embayment rate

= expected number of reembayed craters that will be destroyed

= somewhere between 0 and 1

D = Destruction rate (total)

= Pd * N + DME*Ee

It can be taken as a first approximation that:

$d/dt\ (Ne) = Np * Pe - Ne*Pd - DME * Ee$

$d/dt\ (Np) = C - Np*Pe - Np*Pd$

$d/dt\ (N) = d/dt\ (Ne+Np) = C - N*Pd - DME*Ee$

At equilibrium, $d/dt\ (N) = 0$, yielding :

(For $DME = 0$)

$$C = N*Pd$$

$$N = C/Pd$$

Also, $d/dt\ (Ne) = 0$:

(For $DME = 0$)

$$Np*Pe = Ne*Pd$$

$$Ne = Np*Pe/Pd$$

$$Ne = (N-Ne)*Pe/Pd = N*Ped - Ne*Ped$$

$$Ne\ (1+Ped) = N*Ped$$

$$Ne/N = Pe/(Pd+Pe)$$

(For $DME = 1$)

$$Np*Pe = Ne * (Pd+Pe)$$

$$(N-Ne)*Pe = Ne*(Pd+Pe)$$

$$N*Pe = Ne*(Pd+2Pe)$$

$$Ne/N = Pe/(Pd+2Pe)$$

Evaluating Pe and Pd

A crater is destroyed if it is completely covered. That is, if:

$$R > r + d$$

or:

$$d <= R-r$$

(Where r= crater radius, R= event radius, and d = distance between crater center and event center (all in radians).)

Which says that the event must occur within distance d, corresponding to an area:

$$A=0.5 * (1-\cos [d]) \text{ (in steradians)}$$

A/4PI gives us the probability that a randomly located event will occur in area A, so

$$Pd = 0.5 * (1 - \cos [R-r])$$

Similarly, to embay the crater without destroying it:

$$R-r < d < R+r$$

Using the same formulae for A and probability and simplifying gives us:

$$Pe = 0.5 * (\cos [R-r] - \cos [R+r])$$

As can be seen from its dependences, this derivation of Pe and Pd holds only for a crater of a particular size and a resurfacing event of a particular size. Combining results for craters of multiple sizes must be done carefully. In fact, the difference between the claimed results of *Phillips et al.* [1992] and SimVenus results may derive from a failure to weight different crater sizes appropriately, as no mention of weighting is made in *Phillips et al.* [1992].

APPENDIX B

THE 'END OF DIE-OFF CRITERION'

As discussed in Section 6.3.4, it is difficult to pick an obvious point in the exponential decay model to represent the end of global resurfacing and the beginning of post-GRE resurfacing. In fact, this lack of transition points is perhaps the most distinguishing feature of the exponential model. Nevertheless, if we wish to use the stratigraphic evidence, it is necessary to find such a transition point.

As described in Section 6.3.4, the eventual solution was simply to note the times required to embay varying numbers of craters. However, another solution was used for some time in earlier work. This solution is described here for purposes of comparison.

Definition of α

Since the assumption behind the exponential decay model is that there is a 'background' resurfacing rate towards which the resurfacing rate decays, it is reasonable to divide the resurfacing rate into a steady-state portion and a transient portion. The variable α is defined as the ratio of the transient portion to the steady-state portion.

During the GRE, it is expected that the transient portion will be large compared to the steady-state portion (large α). After the GRE has concluded, it is expected that the transient portion will be small compared to the steady-state portion (small α). The problem comes in deciding at what value of α the transition should occur. The choice is fairly arbitrary; the only value that seems any better than any other is $\alpha=1$ (transient and steady-state portions equal).

The Effect of Varying α

$\alpha=1$ was the criterion used in earlier work. However, due to the arbitrary nature of the choice, a number of runs using other values were performed to see how great an effect the choice had on the final results.

Analytically, since α measures the ratio of the transient portion of the resurfacing rate to the steady-state portion, and since the transient portion is decaying exponentially, it can be seen that even a factor of ten change in α only changes the time of switchover by 3-4 times the decay constant.

Still, this could potentially shift a number of embayments from one time period to the other.

In order to test this effect, SimVenus was run with the exponential time model and the number of craters embayed by the tail end of the GRE was set at 10. As α was varied, the other parameters were adjusted to keep this number. The results are shown in Table B1.

As can be seen, even with the greatest change in α, T1 varies by a factor of 1.6 (or 60 million years), while the percentage of the surface resurfaced during the post-GRE resurfacing drops from 19% to 16%. While the change in T1 is significant, it required a change of α of four orders of magnitude. Given this, the author felt that using $\alpha = 1$ was reasonable and would not have too great an effect on the results.

As a variant approach, runs were made for a variety of decay constants and $\alpha=1$. Then, runs were made with the same parameters except for α, which was varied. The results of this approach are shown in Table B2 for completeness, but are of much less use because the shifting values of E1 (number of craters embayed during the GRE) make it difficult to compare different runs.

Run	α	T1	A2
Alpha0	1.0	8.98e7	0.1931
Alpha1	0.5	9.70e7	0.1883
Alpha2	0.1	1.08e8	0.1778
Alpha3	0.01	1.21e8	0.1713
Alpha4	0.001	1.39e8	0.1616
Alpha5	0.0001	1.43e8	0.1616

Table B1. Effects of varying α, while varying other parameters to keep the number of craters embayed by the GRE fixed at 10.

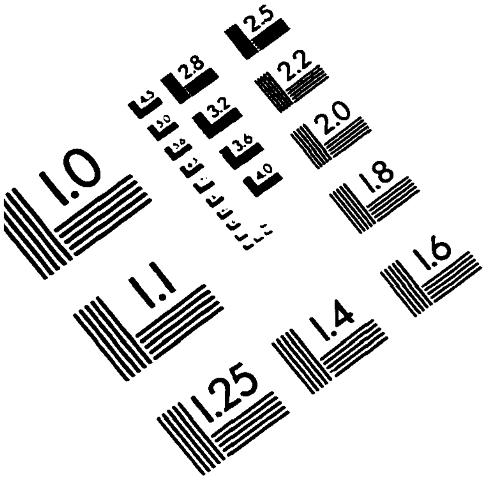
Run	α	E1	T1 (Years)
Exp0	1.0	0.3	4.28e6
Exp0.1	0.5	0.3	4.59e6
Exp0.2	0.1	0.3	5.35e6
Exp0.3	0.01	0.3	6.51e6
Exp0.4	0.001	0.2	7.71e6
Exp1	1.0	0.8	8.35e6
Exp1.1	0.5	0.8	9.13e6
Exp1.2	0.1	0.8	1.07e7
Exp1.3	0.01	0.8	1.30e7
Exp1.4	0.001	0.8	1.53e7
Exp8	1.0	4.6	4.23e7
Exp8.1	0.5	4.7	4.58e7
Exp8.2	0.1	4.8	5.39e7
Exp8.3	0.01	5.1	6.54e7
Exp8.4	0.001	5.3	7.69e7
Exp2	1.0	9.1	8.52e7
Exp2.1	0.5	9.5	9.23e7
Exp2.2	0.1	10.1	1.08e8
Exp2.3	0.01	10.9	1.31e8
Exp2.4	0.001	12.1	1.55e8
Exp3	1.0	18.8	1.74e8
Exp3.1	0.5	21.4	1.90e8
Exp3.2	0.1	22.8	2.22e8
Exp3.3	0.01	25.7	2.68e8
Exp3.4	0.001	29.0	3.14e8

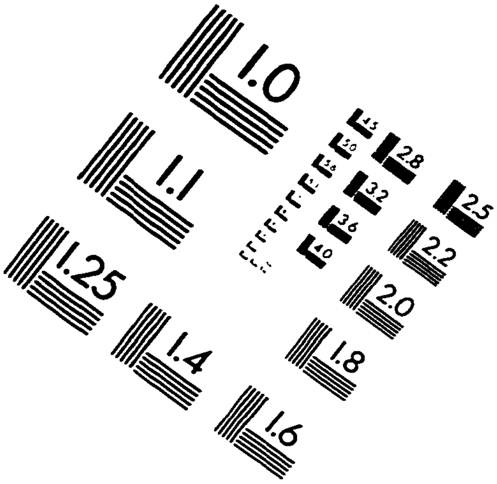
Table B2 (Page 1). Effects of changing α while keeping all other parameters fixed.

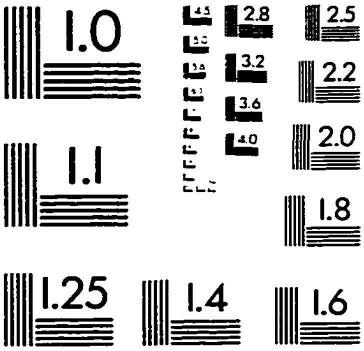
Run	α	E1	T1 (Years)
Exp4	1.0	31.5	2.78e8
Exp4.1	0.5	32.8	2.98e8
Exp4.2	0.1	35.4	3.47e8
Exp4.3	0.01	40.0	4.16e8
Exp4.4	0.001	45.8	4.85e8
Exp5	1.0	42.4	4.05e8
Exp5.1	0.5	43.4	4.33e8
Exp5.2	0.1	45.5	4.97e8
Exp5.3	0.01	48.6	5.83e8
Exp5.4	0.001	48.6	5.83e8
Exp6	1.0	49.4	5.23e8
Exp6.1	0.5	49.9	5.54e8
Exp6.2	0.1	50.4	6.09e8
Exp6.3	0.01	50.4	6.09e8
Exp6.4	0.001	50.4	6.09e8
Exp7	1.0	51.6	6.2e8
Exp7.1	0.5	51.6	6.2e8
Exp7.2	0.1	51.6	6.2e8
Exp7.3	0.01	51.6	6.2e8
Exp7.4	0.001	51.6	6.2e8

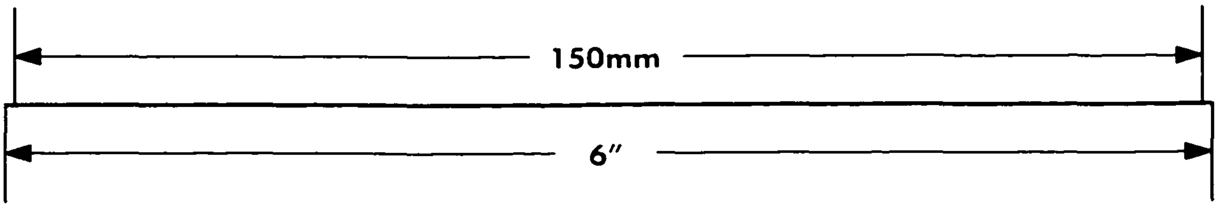
Table B2 (Page 2). Effects of changing α while keeping all other parameters fixed.

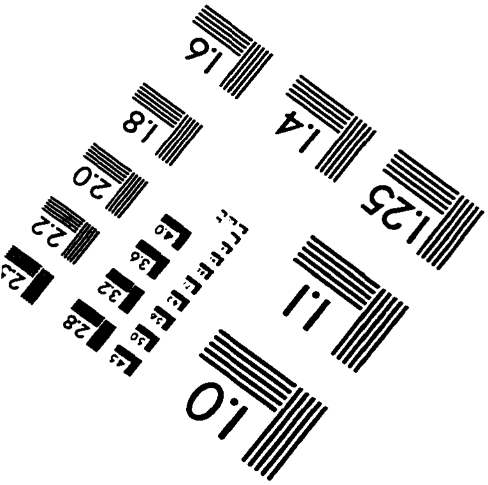
IMAGE EVALUATION TEST TARGET (QA-3)

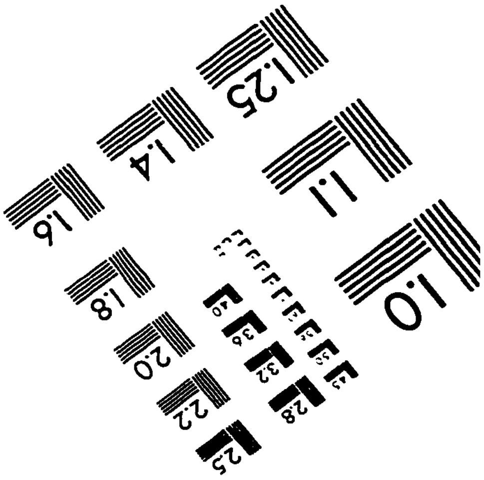












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