GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 16, PAGES 2593-2596, AUGUST 15, 1999

Impact craters on geologic units of northern Venus: Implications for the duration of the transition from tessera to regional plains

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Abstract. Using Magellan SAR images and the *Schaber et al.* [1998] crater data base we examined impact craters in the area north of 35°N and determined the geologic units on which they are superposed. The crater density of the regional plains with wrinkle ridges (Pwr) was found to be very close to the global average and thus the mean surface age of the plains is close to the mean surface age of the planet (T). About 80 to 97% of the craters superposed on a composite unit that includes materials of Tessera terrain (Tt), Densely fractured plains (Pdf), Fractured and ridged plains (Pfr), and Fracture Belts (FB), also postdate the regional plains. Thus, the time interval between the formation of these older units and emplacement of the regional plains (ΔT) should be geologically short, from a few percent to about 20% of T, or approximately 40 to 150 m.y. This means that in the area under study, volcanic and tectonic activity in the beginning of the morphologically recognizable part of the geologic history of Venus (about the last 750 m.y.) was much more active than in the subsequent time.

1. Introduction

The goal of this analysis is to use impact craters as a tool to estimate the duration of several events in the geologic history of Venus. The geology of the northern part of Venus (north of 35°N, representing about 21% of the surface) has been mapped at 1:20M scale as a part of the ongoing Vernadsky/Brown global mapping project [*Basilevsky et al.*, 1998b; 1999] and these data provide a basis for the analysis of the relations of geologic units and superposed impact craters over a significant percentage of the surface. Using digital versions of Magellan C1MIDRPs and the *Schaber et al.* [1998] crater data base, we examined the impact craters in this area, determined the geologic units on which they are superposed, and considered the implications of these data for the stratigraphy and the geologic history of this area. The units include (from older to younger): 1) Tessera terrain material (Tt) combined in this study with the material of mountain belts of the area surrounding Lakshmi Planum; 2) Material of densely fractured plains (Pdf); 3) Material of broadly ridged and fractured plains (Pfr), typically present as fragments of the ridge belts; 4) Material of the fracture belts (FB); 5) Material of shield plains (Psh); 6) Material of plains with wrinkle ridges (Pwr) (in this study we did not subdivide it into Pwr_1 and Pwr_2 subunits); 7) Material of smooth plains (Ps); 8) Material of lobate plains (Pl); and 9) Material of radar-dark mantles (DM). Detailed unit descriptions including unit to unit relations (except DM) can be found in *Basilevsky and Head* [1998a]. DM is radar-dark material typically associated with impact craters. It includes the most prominent parts of the Cdp (material of the dark crater-related parabolic features) unit of *Basilevsky and Head* [1998a] and non-parabolic dark mantles as well.

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Paper number 1999GL008329.
0094-8276/99/1999GL008329$05.00

2. Observations

In this analysis we first examined the image to determine the unit(s) on which the crater is superposed, and only then did we examine the geologic map to assess in which mapped geologic unit the specific crater occurs. In virtually all cases the units seen on the image and shown on the map were the same. Exceptions were when craters were superposed on such small outcrops of some units that the latter were below the 1:20M mapping scale. We discuss below the relations of the units and craters observed on the images. In many cases, the crater under consideration (including its ejecta, related outflows, and radar-dark halo) was found superposed on more than one unit (Figure 1). This is typical for older units which are often present as small islands among the younger plains. In these cases we considered this crater as superposed on the oldest of these given units and noted the youngest unit postdated by this given crater. In this way we determined the areal density of superposed craters for each of the mapped geologic units. The unit areas were determined through counting pixels of each unit on the digital version of the geologic map [for details, see *Ivanov et al.*, 1999]. The results of our photogeologic analysis are given in Table 1.

In our work we consider also cases when craters are embayed by some units in which there is an unequivocal indication that the crater emplacement predated the emplacement of the embaying unit. In six cases embayment of craters and their ejecta from outside was clearly observed. Four craters superposed on Pwr plains were found to be embayed: two by Pl and two by Ps materials. Two craters were found to be definitely embayed by the Pwr materials. Crater Conway, 48.3°N, 39.1°, D=50 km, is superposed on Tt material and embayed from the west by Pwr plains (Figure 2). Crater Heloise, 40°N, 51.9°, D=40 km, is significantly flooded by Pwr material which is partly warped by wrinkle ridges. The unit on which this crater is superposed is not observed. For this reason this crater is not included in the data given in Table 1.

One of the craters in the mapped area shows ambiguous relations with the surrounding geology. The crater Baker, 62.6°N, 40.5°, D=105 km, is superposed on Tt material of southern Fortuna Tessera (Figure 3). Topographic lows inside the crater and within tessera outside of the crater are filled with material appearing to be smooth plains (Ps). Flows of this material are clearly superposed on Pwr plains SW of the crater. No knobby

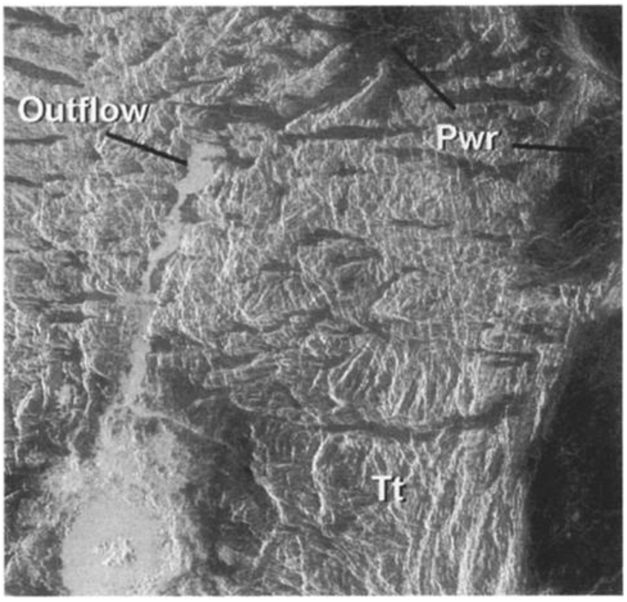

Figure 1. Crater Khatun (D = 40 km) (lower left) superposed on Tt material of Tellus Tessera. Ejecta outflow is superposed on Pwr which embays tessera. In C1MIDRP 45N096;2.

ejecta is seen around Baker. Instead the crater rim appears to consist of fragments of Tt material with its tectonic trends. In our analysis, we find two plausible interpretations of the geologic setting of this crater. One interpretation is that the smooth plains material around and inside the crater is a type of crater outflow, thus implying that the crater was formed after the emplacement of the Pwr plains SW of it. The other interpretation is that the absence of the knobby ejecta of the crater is due to its earlier reworking by tessera-forming deformation so the crater is very old. In this case the smooth plains inside and outside of the crater is a result of late geologic activity in this area not directly related to the crater-forming impact.

3. Discussion

There are only about 1,000 impact craters on the entire surface of Venus [*Schaber et al.*, 1998] and only about 200 craters on the one-fifth of the planet studied in this analysis. Only 51 to 63 of them are superposed on the old units predating the Pwr-Psh regional plains. Among these, 49 to 61 showed a visible influence on the regional plains, covering them by differing types of ejecta: e.g., its hummocky and outflow facies as well as the extended radar dark haloes including crater-related parabolic features. Only 2 to 8 craters are found to predate the end of the plains emplacement while the rest, 49 to 61, postdate the plains emplacement. Although these obviously represent a very small population, we believe that cautious consideration of their distribution is nevertheless worthwhile.

As can be seen from Table 1, all geologic units have craters superposed on them. In most cases the number of craters on the unit is rather small, so the error bars for the crater densities are too large for reliable conclusions: 45 to 57% of the estimated density value for Psh, FB, Pfr, Pdf, Tt, and 75 to 100% for DM, Pl, Ps. The error bars for densities of all these populations overlap. It is evident that it is a problem of statistics of small numbers so to discuss the estimated densities for these units is not realistic. The error bars are rather small only for the total area population and for Pwr plains (14 and 19% of the estimated densities), so these densities have more potential geologic significance. They are very close to the global average (2.01±0.14, [*Price and Suppe*, 1994]). This is evidence that in the sense of the average surface age the area studied is a representative subsample of the whole planet. This also supports, at least for the area studied, our earlier supposition that the surface age of the regional plains, which is essentially plains with wrinkle ridges, should be practically equal to the global average crater retention age of Venus (T) [*Basilevsky et al.*, 1997].

Craters superposed on one of the relatively young units (DM, Ps, Pl) are not superposed on other younger units. Among 106 craters superposed on the Pwr plains only 13 craters (12.3%) were superposed also on units younger than Pwr. For Psh a percentage of craters superposed on the units, younger than the one considered, is 25%, and it increases significantly for the older units: FB - 100%, Pfr - 86%, Pdf - 100%, and Tt - 80%. It is evident that craters superposed on some unit were accumulated during all time from the unit formation until the present. So if the unit is relatively old, both rather old and rather young craters should be among the craters seen on it. The older the unit is, the more are the chances that craters superposed on it will postdate and influence the units younger that the one considered.

Let us consider the ideal case, when all the craters superposed on the older unit after emplacement of the younger unit (their number is N_{post}), had shown visual evidence of their lateness, and that among the craters superposed on the older unit we are able to identify all the craters formed before the end of the younger unit emplacement (their number is N_{pred}). In that case, if the time after the formation of the younger unit is T, and the time interval between the emplacements of the older

Table 1. The Characteristics of Populations of Impact Craters Superposed on the Geologic Units of the Area Under Study

Unit	Unit area, 10^6km^2	Percent of total area	Number of superposed craters	Including those superposed on the younger units	Crater density per 10^6km^2 ± 2σ
DM	2.27	2.3	4	-	1.76 ± 1.76
Pl	5.85	6.0	7	-	1.20 ± 0.90
Ps	1.50	1.5	7	-	4.67 ± 3.52
Pwr	52.03	53.0	106	13: Pl-5, Ps-4, Psh_2*-4	2.04 ± 0.39
Psh	8.94	9.1	12	4: Pl-1, Ps-1, Pwr-2	1.34 ± 0.77
FB	5.36	5.5	12	12: Pl-1, Psh_2-3, Pwr-7, Psh-1	2.36 ± 1.29
Pfr	5.08	5.2	14	12: Pl-3; Ps-1; Psh_2-2; Pwr-5, FB-1	2.76 ± 1.47
Pdf	4.40	4.5	17	17: Dm-1, Ps-1, Psh_2-5, Pwr-7, Psh-2, Pfr-1	3.86 ± 1.87
Tt	12.70	12.9	21	16: Ps-2, Psh_2-2, Pwr-11, Psh-1	1.65 ± 0.72
Total	98.13	100	200		2.04 ± 0.29

* Psh_2 is younger subunit of Psh postdating wrinkle ridges of the Pwr plains.

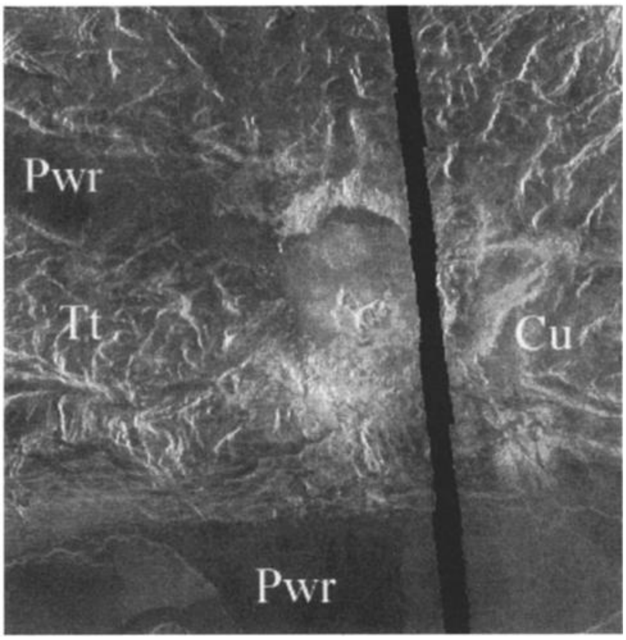

Figure 2. Crater Conway (D = 50 km) evidently superposed on tessera material and partly flooded by Pwr. Area is 147 x 150 km. In C1MIDRP 45N032;201.

and the end of emplacement of the younger unit is ΔT, the ratio $\Delta T/T$ should be equal N_{pred} / N_{post}. This is true, of course, if for the period of time considered the crater-forming flux was approximately constant. The existing literature considers that that was the case [*McKinnon et al.*, 1997, and references therein].

The requirement for determining the visual influence is the spatial proximity of the younger units to this given crater. So if the unit under consideration occupies large areas with rare or no outcrops of younger units within it, the cases of influence on younger units should be rare or absent, even if the unit considered is rather old. This is evidently the case for the Pwr plains. If the unit under consideration forms small islands among the younger unit(s), the latter is an easily available target for the considered influence. This is evidently the case for FB, Pfr, and Pdf. Tessera material, which is present both as large continent-sized regions and as small islands among the younger plains, represents the intermediate case.

To decrease the stochastic errors we combine the three stratigraphically oldest units (Tt, Pdf and Pfr) into one composite unit which occupies 22.18 x 10^6 km^2 (about 22.6% of the area under study). Among 51 craters superposed on the Tt+Pdf+Pfr composite unit, 45 craters belong to a category superposed on the younger units (see Table 1). Among those 45 craters, 43 postdated regional Pwr+Psh plains (whose age is close to T) and in some cases even the younger DM, Ps or Pl materials. Even if all the remaining 8 craters predated the regional plains, this means that the time period between the formation of those relatively old units and the end of the emplacement of the regional plains (ΔT) was rather short, approximately 8/43T (Figure 4). This is definitely the upper limit of the estimate because only for two of those craters do we know (Conway), or suspect (Baker), their pre-(Pwr+Psh) age. The other six might postdate the emplacement of the regional plains, thus decreasing the ΔT to 2/49T.

If this ancient composite unit is added together with the stratigraphically neighboring FB unit, the results are essentially the same. The total area of the combined Tt+Pdf+Pfr+FB composite unit is 27.54 x 10^6 km^2 (28.1% of the area under study). The number of craters superposed on this unit is 63. Among these, 57 craters show a visible influence on younger units and 55 of them are seen to postdate the regional Pwr+Psh plains. The maximum estimate of the craters predating the regional plains is again 8, and the minimum is again 2. This means that the time period between formation of those relatively old units and the emplacement of the regional plains (ΔT) was rather short, from approximately 2/61T to 8/55T (Figure 4).

Among those 51 to 63 craters which are superposed on the older composite units, the minimum and maximum estimates of the number of craters which formed before the emplacement of the regional plains are 2 and 8. These numbers provide the basis for statistically significant conclusions. If we (as do all authors who have worked with the crater statistics issues, e. g. *Price and Suppe*, 1994) will consider that for amount of craters N, its standard deviation δ is a root square of N, then we should compare (in the worst for our conclusions case) 8±3 and 51±7 at the 1δ level, and correspondingly 8±6 and 51±14 at the 2δ level. It is evident that at the 2δ level (95% probability) the first of the numbers considered is much smaller than the second one. Therefore, although the numbers we work with are small, from the statistical point of view our conclusions are rather robust.

But there is another, nonstatistical reason why these estimates should be interpreted cautiously. We have combined three, and then four older units in one composite unit that increased both the area covered by the units and the number of craters, thus decreasing the stochastic variability. As a result, instead of analyzing the specific stratigraphic sequence of geologic units, we assess a combination of them. In the latter case, the weights of each of these units in the

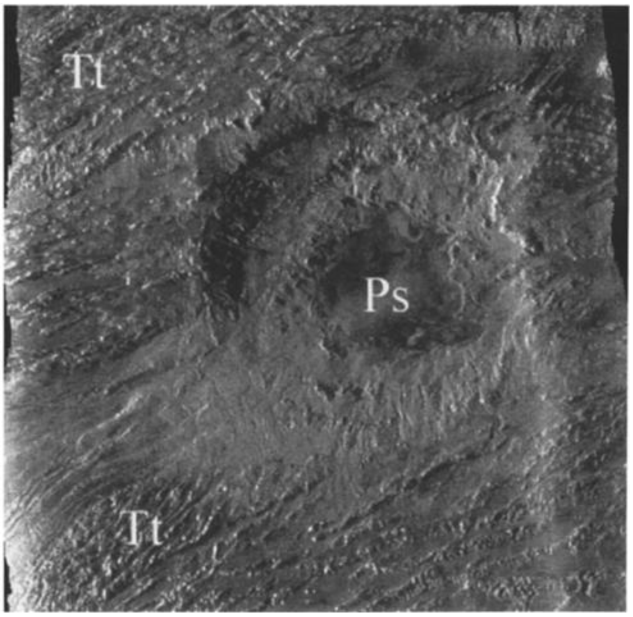

Figure 3. Crater Baker (D = 105 km) superposed on tessera terrain (Tt). Its floor and local depressions outside the crater are flooded by material similar to Smooth plains (Ps). Area is 195 x 200 km. In C1MIDRP 60N042;301.

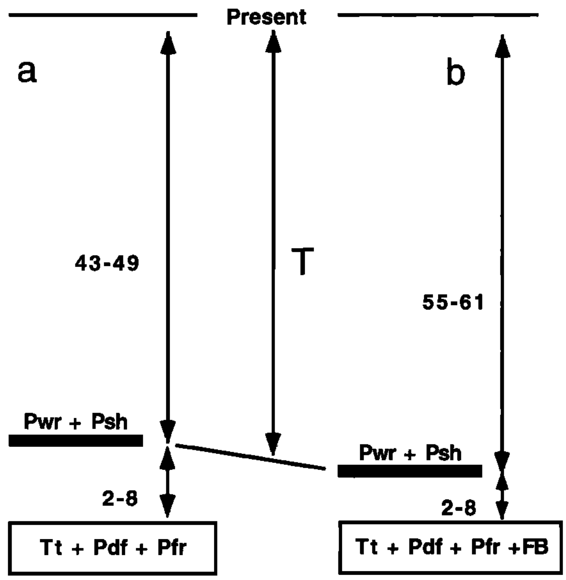

Figure 4. Diagram showing the position of regional Pwr+Psh plains and older composite units along the time axis (vertical). Distances (arrow-headed lines) along the time axis between the positions of "Present", "Pwr+Psh", "Tt+Pdf+Pfr" and "Tt+Pdf+Pfr+FB" are approximately proportional to the numbers of craters superposed on the composite units, including those predating the end of the Pwr+Psh plains emplacement (2-8) and those postdating the plains (43-49 and 55-61).

time/stratigraphic sense are unknown. Thus, it appears that we should avoid numbers with estimated error bars and may say only that if the average age of the regional Pwr+Psh plains of the area studied is T, the time period between formation of the mixture of those relatively old units and the emplacement of the regional plains (ΔT) was probably more than a few percent and less than about 20% of T.

The conclusion that ΔT is only a specific and rather small portion of T is evidently correct for the area studied as a whole, but not necessarily for the individual occurrences. In relation to local stratigraphic columns in this area it means that the proportions between the ages of the group of younger (post-Pwr+Psh) units and the ages group of older (Tt+Pdf+Pfr±FB) plus (Pwr+Psh) units may be different at different places. However this variability is constrained by the established fact that in the total population of craters superposed on the older units, the number of craters predating the end of emplacement of the Pwr+Psh plains is significantly smaller than number of craters postdating the plains. This, in turn, means that in the majority of the sub-areas in the area studied, ΔT should be significantly shorter that T. Otherwise the observed small ratio of pre- and post-(Pwr-Psh) craters on the old composite unit(s) could not be the case.

In recent work, *McKinnon et al.* [1997] came to the conclusion that the best estimate of the average surface age of Venus (T) is about 750 m.y., although any age between 300 m.y. and 1 G.y. is plausible. If we rely on this estimate, ΔT should be about 40 to 150 m.y. If we consider the extremes, ΔT may be from about 15 to 200 m.y. These data thus provide an estimate of the time of the transition from the emplacement of the combined unit (Tt, Pdf, Pfr, FB) to emplacement of the much less intensely deformed regional plains (Psh + Pwr). Together these units occupy more than 90% of the area under study. During the subsequent time, the duration of which might be 260 to 850 m.y., the younger units (DM, Pl, Ps) occupying altogether less than 10% of the area studied, were formed. This means that volcanic and tectonic activity in the beginning of the morphologically recognizable part of the geologic history of Venus was much more active than in the subsequent time. This conclusion generally supports models of the geologic history of Venus that require major changes in rates and styles over relatively short periods of time [e.g., *Strom et al.*, 1994].

4. Conclusions

The crater density of the regional plains with wrinkle ridges (Pwr) in the area north of 35°N is close to the global average; thus its mean surface age is close to the mean surface age of Venus (T). Because the predominant majority (about 80 to 97%) of craters superposed on Tessera terrain (Tt), Densely fractured plains (Pdf), Fractured and ridged plains (Pfr), and Fracture Belts (FB), also postdate the regional Pwr+Psh plains, the time interval between the formation of these older units and the emplacement of the regional plains (ΔT) should be rather short, from a few percent to about 20% of T, or approximately 40 to 150 m.y. These findings imply a rather active beginning of the morphologically recognizable part of the geologic history of Venus and relative quiescence in the subsequent geologic activity, providing further constraints for geophysical models of the evolution of Venus.

Acknowledgements. Comments from M. Kreslavsky and reviews by Maribeth Price and two anonymous reviewers improved the paper. This work was supported by a grant from the NASA PG and G Program (NAG5-4585) to JWH.

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(Received March 2, 1999; revised May 20, 1999; accepted June 17, 1999.)