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Venus: Estimation of age of impact craters on the basis of degree of preservation of associated radar-dark deposits

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[1] Venus impact craters larger than 5 km in diameter (~90% of all craters) have been classified based on the presence and prominence of associated radar-dark deposits. Approximate estimates of the absolute age of craters of different morphologic classes are made. Analysis of age relations of dated craters and volcanic and tectonic structures permits the estimation of the age and duration of different volcanic and tectonic events. *INDEX TERMS:* 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5475 Planetology: Solid Surface Planets: Tectonics (8149); 5480 Planetology: Solid Surface Planets: Volcanism (8450). **Citation:** Basilevsky, A. T., J. W. Head, and I. V. Setyaeva, Venus: Estimation of age of impact craters on the basis of degree of preservation of associated radar-dark deposits, *Geophys. Res. Lett.*, *30*(18), 1950, doi:10.1029/2003GL017504, 2003.

1. Introduction

[2] Venus has only about 1,000 impact craters, enough to estimate the mean global surface age of this planet [*Schaber et al.*, 1992; *Phillips et al.*, 1992; *Strom et al.*, 1993; *McKinnon et al.*, 1997] and the mean ages of a few areally extensive geologic units [*Ivanov and Basilevsky*, 1993; *Price and Suppe*, 1994; *Namiki and Solomon*, 1994], but not enough to date individual geologic structures. This is partly compensated for by the opportunity to estimate approximately the age of individual impact craters, and then the age of neighboring geologic units and structures. This approach is based on analysis of the Magellan images and evaluation of the presence and degree of preservation of radar-dark deposits [*Arvidson et al.*, 1992; then *Basilevsky*, 1993; *Strom*, 1993; *Herrick and Phillips*, 1994; and *Izenberg et al.*, 1994]. The latter two references considered craters with associated dark parabolic features, craters with non-parabolic halos, and craters with no associated halos as an aging sequence. From percentages of craters of these three categories on the plains, *Izenberg et al.* [1994] concluded that the age of craters with dark parabolas is smaller than ~0.1T, the age of craters with non-parabolic halos is ~0.1 to 0.5T, and the age of craters with partial halo and no halo is >0.5T, where T is mean global age of Venus' surface (estimated by several researchers as 0.5–1 b.y. [*Schaber et al.*, 1992; *Phillips et al.*, 1992; *Strom et al.*, 1993; *McKinnon et al.*, 1997]).

[3] This approach was recently further developed by *Basilevsky and Head* [2002] who subdivided craters into three groups: 1) those superposed on wrinkle-ridged regional plains whose age is close to T, subpopulation 1; 2) superposed on units younger than regional plains, subpopulation 2; and 3) others, including superposed on units older than regional plains, craters heavily flooded by lava that precluded understanding of superposition, and craters not imaged by Magellan. *Basilevsky and Head* [2002] suggested a four-member crater classification be used: 1) craters with dark parabolas (DP), 2) with clear halo (CH), 3) with faint halo (FH) and 4) with no halo (NH) (Figure 1). This study was done for all 188 Venusian craters ≥30 km in diameter.

[4] That work assessed whether the DP, CH, FH and NH percentages of the combined subpopulations 1 and 2 were dependent on the geographic latitude and on crater size. No reliable correlations were found. Following this, the percentages of the DP, CH, FH and NH craters for subpopulation 1 were determined and theoretical models were developed to show how these percentages depend on the lifetime of crater-associated dark deposits for two end-member cases: 1) all wrinkle-ridged regional plains of Venus were emplaced within a relatively short interval of time (synchronous case) and 2) regional plains in different areas of Venus were emplaced at different times (non-synchronous case). It was found that for the synchronous case and partly for the non-synchronous case (if the time interval of the regional plains emplacement was not larger than ±0.5T) the DP craters are younger than 0.1–0.15T, the age of the CH craters is from 0.1–0.15 to 0.5T, and the age FH and NH craters is larger than 0.5T.

[5] These estimates, which agree well with the above cited estimates of *Izenberg et al.* [1994], were applied to dating several key geologic structures of Venus [see details in *Basilevsky and Head*, 2002]. For subpopulation 2, the DP, CH, FH and NH crater percentages determined suggested approximately constant rates of volcanic and tectonic activity in post-regional-plains time. *Basilevsky and Head* [2002] studied only craters ≥30 km in diameter (19.4% of the impact craters of Venus) so it was not clear to what extent the results obtained were applicable to craters of smaller size. In particular, the relatively small number of craters ≥30 km in diameter decreased the ability to date geologic units and structures.

[6] In the present work we have studied all craters ≥5 km in diameter: 854 craters, 89.3% of Venus' crater population. We did not study craters smaller than 5 km partly because their details are comparable in size with the Magellan image resolution and partly because around this size the cratering

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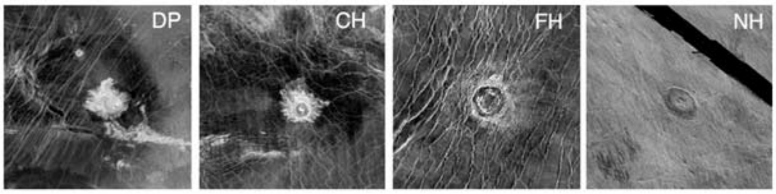

Figure 1. Morphologic classes of craters: DP, with dark parabola (crater Stuart); CH, with clear dark halo (Caccini); FH, with faint halo (Barrymore); with no halo (Erina).

event is different than larger impacts [*Ivanov et al.*, 1992; *Schultz*, 1992].

2. The Data Analysis

[7] All 854 craters $\geq$5 km in diameter listed in database of *Schaber et al.* [1998] were first subdivided into subpopulation 1 (541 craters superposed on wrinkle-ridged regional plains), subpopulation 2 (212 craters superposed on the younger units) and others (101 craters) (Figure 2).

[8] Then craters of subpopulations 1 and 2 were classified into DP, CH, FH and NH classes. Some craters and their surroundings have been found to be obscured by dark deposits of other craters, regional dark mantles and sometimes by young lava. So these craters cannot be classified and in *Basilevsky and Head* [2002], a fifth class - "Obscured" - was introduced. Among 753 craters of subpopulations 1 + 2, there are 51 craters (7%) of class DP, 223 craters (30%) of class CH, 224 craters (30%) of class FH, 140 craters (18%) of class NH and 115 obscured craters (15%). This is rather close (except DP) to the percentages found for craters $\geq$30 km.

2.1. Latitude Dependence Test

[9] A latitude dependence may potentially exist because of changes in visibility due to variation of radar incidence angle as a function of latitude [*Ford et al.*, 1993]. Furthermore, eolian resurfacing and thus dark deposit lifetime may also be latitude dependent because of differences in atmosphere circulation at low and high latitudes of the planet [*Gierash et al.*, 1997]. For this test the studied population was subdivided into five parts, each corresponding to one of five equal area (1/5 of the planet's surface) latitude zones (Figure 3). It is seen from Figure 3 that the subpopulation studied, which is much larger than previously studied (753 vs. 168), does not show a noticeable latitude effect in the percentages of craters of different classes, especially if we apply to the analysis the $\pm\sqrt{N}$ confidence level appropriate for the Poisson distribution.

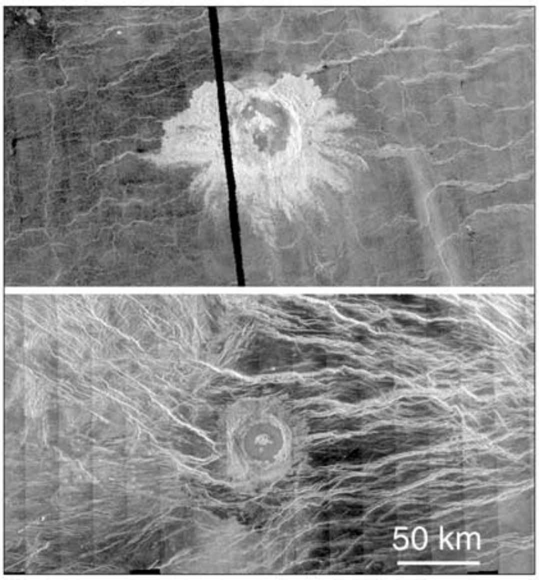

Figure 2. Top, crater Barto superposed on wrinkle-ridged regional plains. Bottom, crater Sitwell superposed on the young rift zone.

2.2. Test for Size Effect

[10] This effect was not found for craters $\geq$30 km in diameter. But *Campbell et al.* [1992] reported that dark parabolas were observed in association only with craters $\geq$12 km in diameter (11.4 km according to measurements of *Schaber et al.*, 1998). So it is logical to expect the existence of a size effect for other crater classes considered. For this test we sorted craters of the combined subpopulations 1 + 2 into five size intervals each containing approximately the same number (150 to 153) of craters.

[11] It is seen from Figure 4 that for the combined subpopulation considered the size effect is obvious for the DP class: Along with the crater size decrease the DP percentages decrease. For other classes no noticeable size effect is seen, probably because of stochastic noise due to the small number of craters of each given class in the considered size intervals.

[12] To decrease the stochastic noise, we subdivided the crater subpopulation 1 + 2 into a smaller number of size intervals (4, 3, 2) containing a proportionally larger number of craters. For subdivisions into four and three equal crater number size intervals, some trends for the CH, FH and NH

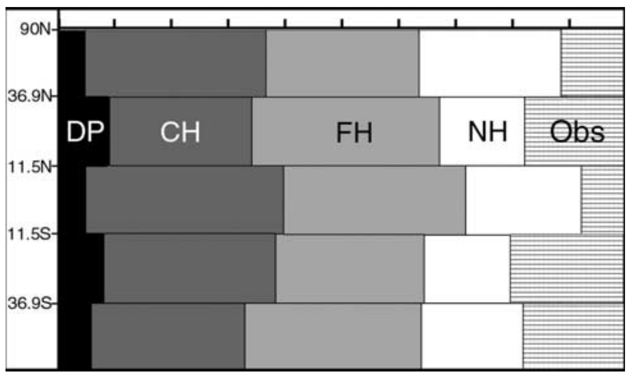

Figure 3. Percentages of DP, CH, FH, NH and the Obscured craters for 5 latitudinal zones of Venus.

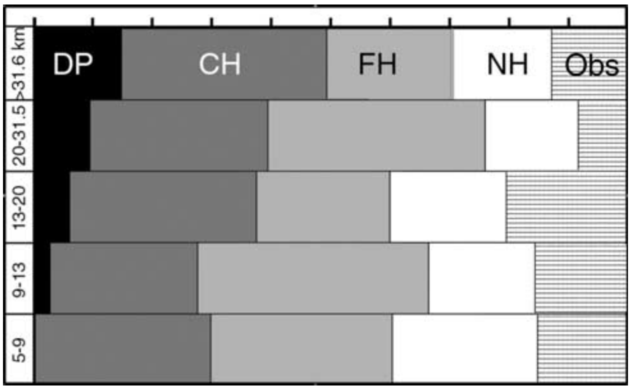

Figure 4. Percentages of DP, CH, FH, NH and the Obscured craters for 5 size intervals.

classes started to be seen, but the most obvious picture is seen when subdivision into two equal number size groups is used. The boundary crater diameter for this subdivision is 15.8 km. This diameter value also has significance for the abundance of DP craters: for craters >15.8 km the abundance of DP craters varies around 12–13%, then it falls sharply, and among craters <11.4 km in diameter the DP class is absent.

[13] In the subsequent analysis we considered separately craters of subpopulations 1 and 2. Craters of the "Obscured" class were sorted out and only craters of DP, CH, FH and NH classes were considered, so their percentage sum was 100%.

2.3. Subpopulation 1

[14] Shown in Table 1 are percentages of craters of the DP, CH, FH and NH classes in the whole subpopulation 1 (465 craters) and when it is subdivided into two size intervals with the 15.8 km and 11.4 km (no DP below this size) boundary diameters.

[15] For smaller craters, in addition to a sharp decrease in DP abundance, some increase of the percentages of FH and NH craters is observed, while the percentage of CH craters is not changed or slightly decreases. As shown by *Basilevsky and Head* [2002], the percentages of DP, CH, FH craters in subpopulation 1 are proportional to the lifetimes of these crater classes. So rounding numbers we may conclude that for craters >11 km in diameter, the age of DP craters is $\leq$0.1–0.15T, the age of CH craters is 0.1–0.15T to 0.5T, the age of FH and NH craters is >0.5T; and for craters <11 km in diameter, the age of CH craters is $\leq$0.3T and the age of FH and NH craters >0.3T.

2.4. Subpopulation 2

[16] This subpopulation includes 182 craters ("Obscured" excluded) superposed on units younger than regional plains (Table 2). The mean age of these units is close to 0.5T [*Price and Suppe*, 1994; *Namiki and Solomon*, 1994]. So it was expected that compared to subpopulation 1 the percentages of the younger morphologic classes (DP and CH) in subpopulation 2 would noticeably increase while percentages of the older classes (FH and NH) would decrease. Surprisingly the observations showed that percentages of all four classes in subpopulation 2 were almost indistiguishable from those of subpopulation 1.

Table 1. DP. CH, FH, NH Crater Percentages in Subpopulation 1

Size, km	Percentage, %			
(No. of craters)	DP	CH	FH	NH
5–270 (465)	7	35	37	21
15.8–270 (232)	13	35	31	21
5–15.8 (233)	1	35	42	22
11.4–270 (309)	11	36	34	19
5–11.4 (156)	0	32	41	27

Table 2. DP. CH, FH, NH Crater Percentages in Subpopulations 1 and 2

Subpopulations	Percentage, %			
(No. of craters)	DP	CH	FH	NH
Subpop. 1 (465)	7	35	37	21
Subpop. 2 (182)	9	34	35	22

[17] After consideration of the characteristics of the units on which craters of subpopulation 2 are superposed, and the characteristics of subpopulation 2 itself, we suggest that in addition to the factor of the younger age, two other factors obviously influence the DP, CH, FH, NH percentages in this subpopulation. Factor 1 is related to the fact that a significant portion of the post-regional-plains units is represented by lobate plains and rifted terrain, both typically radar bright (Figure 5). Halos superposed on these units look less dark than on the neighboring regional plains or even not seen at all. A similar effect is observed for halos superposed on tessera terrain. This observational effect, also noticed by other researchers [see e.g., *Izenberg et al.*, 1994] should increase the percentages of classes FH and NH and decrease the percentages of classes DP and CH.

[18] Factor 2 is also related to the brightness of the lobate plains and rift zones. Their brightness not only makes the halo less prominent but also makes the craters themselves more difficult to see and identify. Elements important for identification (rim, ejecta, central peak) are typically radar bright. Thus they are well seen on relatively dark units and with much more difficulty on bright units. Again this effect acts also in the case of craters on radar-bright tessera being responsible for the deficit of small craters on the tessera terrain [*Ivanov and Basilevsky*, 1993]. Factor 2 should be more efficient for craters of smaller sizes and for FH and NH classes. In relation to the crater class percentages

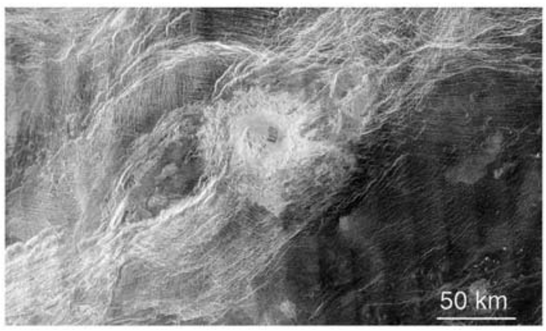

Figure 5. Crater Beecher superposed on radar bright rift. The associated halo looks prominent (CH) on the neighboring plains and is hardly seen (FH) or is absent (NH) within the rift.

Table 3. The Effects of Factors of Younger Age and Brighter Units on the Morphologic Class Percentages in Subpopulation 2

Morphologic classes	Effect on DP, CH, FH, NH percentage		
	Smaller age	Factor 1	Factor 2
DP and CH	Increase	Decrease	Increase
FH and NH	Decrease	Increase	Decrease

considered this factor should decrease the number of identified craters of classes FH and NH, thus decreasing their percentages and increasing the percentages of classes DP and CH. The suggested changes caused by these three factors are shown in Table 3. The net effect of these three factors depends on the effectiveness of each of them. The observation that the DP, CH, FH, NH percentages of subpopulation 2 are close to those of subpopulation 1 means that factor 1 is powerful enough to balance the influence of both the factor of younger age and factor 2.

3. Discussion and Conclusions

[19] The observations show that for craters $\geq$5 km in diameter their geographic latitude does not noticeably affect the visibility of the associated dark halo. This is probably because the radar incidence angle for Magellan did not reach the values which would significantly change their visibility. The absence of a noticeable latitude effect implies also that near-surface winds responsible for the degradation of crater-associated halos work at all latitudes with approximately the same effectiveness.

[20] The most obvious part of the size effect, the absence of the DP craters $\leq$11.4 km in diameter, is probably because relatively small crater-forming events do not produce parabolas [*Campbell et al.*, 1992; *Schultz*, 1992; *Vervack and Melosh*, 1994]. The increase of percentages of FH and NH classes for the smaller craters (FH + NH = 64 vs. 52 and 68 vs. 53 for the 15.8 and 11.4 km boundary diameters) indicates that their associated dark deposits degrade faster than in larger craters.

[21] The results of analysis of craters superposed on wrinkle-wridged plains (subpopulation 1) shows that the estimates of the absolute ages found earlier for craters $\geq$30 km in diameter [*Basilevsky and Head*, 2002] are applicable to craters down to 11 km in diameter, thus significantly increasing the potential of dating of different units and structures on Venus. The estimates obtained for craters of 5 to 11 km in diameter increase this potential even more.

[22] The results of analysis of craters superposed on the younger units (subpopulation 2) show that in the case of radar bright units, dating should be made with caution and the presence of an apparently faint halo or even the absence of halo may not be evidence of old age.

[23] With the new results obtained in the present study, we revisit the Beta-Devana structure. In this region are observed 5 impact craters affected by associated volcanic and tectonic activity: Balch, 40 km in diameter, NH, cut by the Devana rift; Sanger, 84 km, CH, cut by the rift; Raisa, 13.5 km, FH, superposed on early and embayed by later Theia Mons lavas; Olga, 15.5 km, CH, superposed on early and cut by later rift faults; Tako, 10.5 km, FH, superposed on rift faults. Based on these observations *Basilevsky et al.* [2002] concluded that at least part of volcanic and tectonic activity of this structure occurred after 0.5T ago. This conclusion was mostly based on analysis of relations between crater Sanger and the rift faults. The significance of the age relations of craters Raisa, Olga and Tako, all <30 km in diameter, with neighboring geologic structures was unclear. With these new results we confirm the previous conclusion of the relative youth (<0.5T) of the Beta-Devana structure and add that it was already active before the time 0.5T ago (see crater Raisa). This example thus illustrates that with the increased number of craters which now can be used for dating, the age of many geologic features and units on Venus can be estimated.

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