The Impact Crater Density on Volcanoes and Coronae on Venus: Implications for Volcanism and Global Resurfacing;

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Introduction. Volcanic features are widely distributed over the surface on Venus [1], and their ages provide critical information on the magmatic budget of the planet. However, the generally low density of impact craters on Venus, a result of atmospheric shielding [2,3], has prevented a comparison of crater retention ages of small regions [4] and contributes to the controversy over whether a catastrophic [2] or an equilibrium model [3] better describes the global resurfacing history. The spatial diversity of the crater distribution has nonetheless been addressed by grouping areas by latitude [2], radar cross section [3] , or elevation [5]. Following this practice, we integrate the areas and cratering records on large volcanoes and also on coronae, and we assess the implications of the results for volcanism and global resurfacing.

Data Sources. We make use of a data base [5] of 838 impact craters classified according to tectonic deformation and exterior embayment. A data base for 175 volcanoes at least 100 km in diameter [6] has been compiled from Magellan images and a published map [1]. The radius and relief of the edifice and the radius of a radial flow apron are included. A data base for 362 coronae [7] includes classification by feature type and volcanic category. It should be noted that there are 44 features listed in both the volcano and corona data bases.

Crater Density on Volcanoes and Coronae. For large volcanoes, the occurrence of one or more impact craters on the edifice or flow apron is ascertained from the data bases, and the superposition relationships are verified from Magellan radar images. We include the edifice and discernible radial flows in calculating the area of each volcano. We do not count an embayed crater on the plains exterior to a volcanic edifice because it is not generally possible to determine whether the impact occurred before or during the interval of volcanic activity. Thus the crater density for large volcanoes corresponds to the average time when major eruptions ceased. The average density of impact craters on large volcanoes (total area 2.7×10^7 km^2) is $(1.0 \pm 0.2)\times10^{-6}$ km^{-2}, significantly less than the global average of 2.0×10^{-6} km^{-2} [2]. It is unlikely that the obtained crater density is underestimated by missing a large population of old volcanoes because identification of volcanoes should not be biased by age estimation.

For coronae, we determined the crater density only within corona interiors (total area 2.7×10^7 km^2) and obtained $(1.7 \pm 0.3)\times10^{-6}$ km^{-2}. Artemis, the largest corona on Venus, occupies nearly 15% of the total area of coronae and includes 5 craters. The crater density for coronae excluding Artemis ($1.8 \pm 0.3 \times10^{-6}$ km^{-2}) is, however, little changed.

Rates of Volcanic Resurfacing. For a global average surface age of 500 My [2,3], the rate of resurfacing by large volcanoes is 0.05 km^2 yr^{-1}. This figure underestimates the overall volcanic resurfacing rate because many other types of volcanic landforms occur on Venus [1]. If we assume that all embayed craters can be attributed to volcanic activity and that the density of partially embayed craters is a constant for all volcanic deposits, then the area of volcanic flows capable of manifesting an embayment relationship in Magellan images is 1.0×10^8 km^2 and the global volcanic resurfacing rate is 0.2 km^2 yr^{-1}.

Thickness of Flow Units and Magmatic Flux. Large craters are more resistant to volcanic embayment than small craters, and should therefore have a higher ratio of partially embayed craters. In Figure 1 we show the fraction of embayed craters versus crater diameter [5]. The distinct increase in this fraction at a diameter near 30 km is likely because craters larger than this size tend to survive volcanic embayment. The depth of a 30-km-diameter crater on Venus is 1.3-1.8 km [5], and from scaling fresh lunar craters [8] the rim height for such a crater is 1.2 km. If 2 km is the maximum thickness of embaying flow units and the total area of such lava flows is 1.0×10^8 km^2, the maximum volume of such flow units is 2.0×10^8 km^3. For a ratio of intrusive to extrusive magmatism of 10 [9], upper bounds on the total volume of magmatic material and the magmatic flux over the last 500 My are 2.2×10^9 km^3 and 4.4 km^3 yr^{-1}, respectively. The latter

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figure is in agreement with the current rate of volcanism on Venus (0.4 to 11 km^3 yr^{-1}) estimated from the rate of reaction of atmospheric SO_2 and surface carbonates [10].

Corona Resurfacing. Overall, the crater density on coronae is not significantly different from the global average. Coronae have been classified into five groups on the basis of morphology and postulated evolutionary stage [7,11]. The first group, radial and radial/concentric coronae, are held to correspond to the earliest stage of corona formation. The second to fourth groups (categories 1, 2, and 3 [7]) are distinguished by an increasing intensity of volcanism and are held to represent successive evolutionary stages. The last group, corona categories 2r and 3r [7], are held to be the oldest on the basis of their embayment by regional plains deposits. The crater density for each group is shown in Figure 2.

While the small numbers of craters prevent quantitative discussion with high confidence, the crater densities of category 2 and 3 coronae appear less than those of radial and category 1 coronae. If the postulated evolutionary model [7,11] is correct, this result implies that the rate of formation of coronae has not been steady over the past 500 My. If the rate were steady, crater densities in coronae at early stages (radial and category 1) would be less than those at the late stages (categories 2 and 3). The crater densities instead suggest that radial and category 1, 2r and 3r coronae represent features that for the most part ceased to evolve about 500 My ago. The lesser crater densities of category 2 and 3 coronae likely indicate volcanism that lasted until several hundred million years later. While it is possible that the deformation accompanying the formation of radial and category 1 coronae has not removed craters, the population of deformed craters in such coronae (20-25%) still argues against a young age for these features.

Implications for Global Resurfacing. In the end-member equilibrium resurfacing model, the total number of impact craters on the surface should be the result of a balance between crater production and resurfacing. Assuming that such an equilibrium also holds between the volcanic flux and global resurfacing, the crater densities on volcanoes and coronae are predicted to equal the global average density regardless of the mix of global resurfacing mechanisms or the rate of volcanic activity. This result would also hold if volcanoes and coronae formed at the time of a catastrophic global resurfacing event. Thus our results are inconsistent with the simplest end-member models for global resurfacing on Venus and suggest that large volcanoes and coronae with associated volcanic flows have been magmatically active over much of the last 500 My.

References. [1] J.W. Head et al., *JGR*, *97*, 13,153, 1992; [2] G.G. Schaber et al., *JGR*, *97*, 13,257, 1992; [3] R.J. Phillips et al., *JGR*, *97*, 15,921, 1992; [4] J.J. Plaut and R.E. Arvidson, *JGR*, *93*, 15,339, 1988; [5] R.R. Herrick and R.J. Phillips, *Icarus*, submitted, 1993; [6] P.J. McGovern et al., unpublished, 1993; [7] E.R. Stofan et al., *JGR*, *97*, 13,347, 1992; [8] R.J. Pike, in *Impact and Explosion Cratering*, Pergamon, 489, 1977; [9] J.A. Crisp, *J. Volcan. Geotherm. Res.*, *20*, 177, 1984; [10] B. Fegley, Jr., and R.G. Prinn, *Nature*, *337*, 55, 1989; [11] S.W. Squyres et al., *JGR*, *97*, 13,611, 1992.

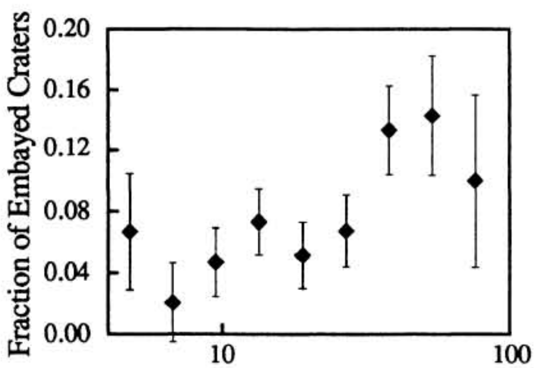

Figure 1. Fraction of embayed craters versus crater diameter. Data from [5].

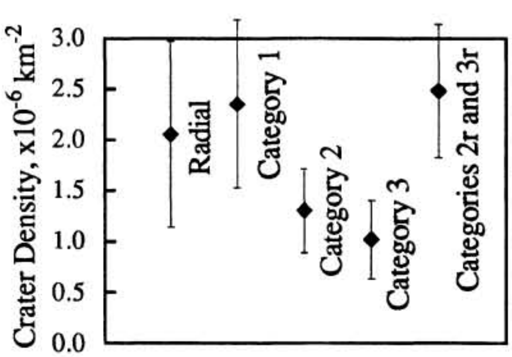

Figure 2. Crater densities on coronae by corona class [7].