Criteria for determination of volcanic embayment of impact craters on Venus:

G. C. Collins and J. W. Head, Dept. of Geological Sciences, Brown University, Providence, RI 02912

Modification of Venusian impact craters by volcanic activity is a crucial issue for constraining the resurfacing history of the planet and the age of the surface. Two groups [1,2,3,4] have used the observation that very few craters have been modified by volcanism as the basis for their models of resurfacing. Each of these groups had an independent data set of craters interpreted to be embayed by volcanic flows. The data sets basically agree on how many craters are embayed, but the agreement on which craters are embayed was only at about the 50% level. Classifying craters as "embayed" or "not embayed" from Magellan radar images is a difficult issue, as one finds many ambiguous situations. The approach of the observer thus becomes an important factor, as evidenced by this disagreement about embayed crater lists, so the criteria that one uses to classify a crater need to be examined. Neither of these groups explicitly outlined their criteria for deciding whether or not a crater is embayed. In preparation for the reanalysis of the Venus crater population, we have developed a list of specific criteria which are discussed below.

Breach of rim: The breaching of a crater rim by a volcanic flow is the most obvious and least disputed evidence for embayment. This is most well-pronounced when the flows are bright and lobate, so the actions of individual flows can be discerned. The situation becomes less clear when a crater seems to have been breached by a radar-dark flow. Two pitfalls may occur here. The first is whether the dark material in question is a smooth volcanic flow or a deposit of fine-grained material, which may appear radar-dark. For instance, the crater Alimat (29.6°S, 205.9°) seems to be breached by dark material, which is actually fine-grained ejecta from the crater Isabella. The second caveat has to do with craters generated by oblique impactors. Such craters on Venus have an uprange zone of avoidance free of ejecta which can also be the site of deposition of fine-grained material during recovery winds after the impact [5]. On some craters, this dark, smooth, ejecta-free area lines up with the part of the crater wall that is foreshortened by the radar geometry, giving the illusion that the rim is breached by dark material.

Dark floored craters: Many craters on Venus have dark, smooth floors. This could be due to the enhanced production of impact melt in Venusian craters [6] which, combined with the high surface temperature, creates thick deposits of melt in the floor of craters that is able to cool slowly, producing a smooth surface. However, craters with dark floors seem to be older in general than bright-floored craters, based on the lack of "pristine" features such as parabolic ejecta or an extensive dark halo [7]. Dark-floored craters are also shallower on average by a few hundred meters [8]. These observations would suggest that the crater is being filled with the dark material over time. This material could be fine-grained material trapped in the aeolian sink of the crater's pit, or it could be smooth, low-emissivity [9] volcanic flows erupted within the floor. If the dark floors were truly volcanic in origin, this would indicate that volcanism on Venus has been more chronologically and areally extensive than some models would predict. Since the dark-floored craters seem to have only a small volume of volcanic fill, it would not represent a major amount of resurfacing, but this type of pervasive small-scale activity would have to be accounted for in the resurfacing models.

Embayment of extended ejecta deposits: One effect of the cratering process on Venus is the creation of a halo of dark material around the crater. This halo is a thin deposit of fine-grained material [10], and as such may be removed by wind erosion over time [7]. Though a crater may lack a dark halo, that does not necessarily mean the halo has been removed by volcanic flows. The appearance of volcanic flows also degrades over time, with bright, digitate

Crater Embayment Criteria: Collins, G. C., and Head, J. W.

flows darkening and losing their definition and details. This is probably due to the same aeolian processes that remove the dark halo, with the deposition of fine-grained material on top of the lava flow masking its roughness over time. Lava flows can also be darkened by being within the range of a dark halo as it forms. In these cases there is noticeable darkening of the flow as it approaches the edge of the ejecta, especially when the image is enhanced for contrast, a good example being the flow near the crater Lind (50.3°N, 355°). The removal of the halo and the loss of detail on lava flows are likely to take place on similar time scales, so if a fresh lava flow is observed within the dark halo without becoming darkened itself, it is likely to be younger than the crater. For example, many details of lava flow textures are preserved around the crater Boivin (4.3°N, 299.5°) without any visible darkening by fine-grained ejecta, so the flows should be younger than the crater.

Embayment of continuous ejecta: It would be useful for the purpose of finding embayed craters if it could be easily determined whether the continuous ejecta of the crater has been partially buried by lava. One could use the variation in area covered by bright ejecta to find craters which have had some ejecta covered by volcanic flows, but there is so much variability in ejecta area among pristine craters that this is not useful. Bright volcanic flows can be seen in some cases abutting against ejecta, such as at the crater Melba (4.7°N, 193.4°), but care must be taken that these flows are not confused with the crater's own run-out flows. Bright lava flows are sometimes diverted around a crater without touching the bright ejecta, possibly by the lobes of fine-grained ejecta around the edges of the bright ejecta, as is the case around the crater Bashkirtseff (14.7°N, 194°). Embayment of ejecta by dark lava flows is much more difficult to discern because of the presence of fine-grained ejecta. Feathery boundaries on ejecta lobes and smooth dark patches in the ejecta blankets are common on Venusian craters. They could be due to pooling of lava in the ejecta blanket, but there are many disconnected patches and no good evidence of flow into or out of the patches. A more likely explanation for this dark material is accumulation of fine-grained ejecta in patches due to recovery winds from the impact event or later wind patterns, or the fine-grained ejecta could be originally deposited with the blockier ejecta in the case of feathery boundaries.

Conclusion: It is important to directly address and concentrate on the criteria that one uses for classification of these craters, since many of their features are subject to different interpretations. If, for example, dark floors in craters and dark patches in ejecta blankets can be demonstrated to be of volcanic origin, this would have a large effect on the extent of volcanism though time in the history of Venus. An example of how some of these criteria may be used and preliminary results of a resurveying effort are reported in Collins *et al.*, this volume.

References: [1] Phillips, R. J., *et al.*, *JGR*, 97, 15,923-15,948, 1992; [2] Schaber, G. G., *et al.*, *JGR*, 97, 13,257-13.302, 1992; [3] Herrick, R. R., and Phillips, R. J., *Icarus*, 111, 387-416, 1994; [4] Strom, R. G., *et al.*, *JGR*, 99, 10,899-10,926, 1994; [5] Schultz, P. H., *JGR*, 97, 16,183-16,248, 1992; [6] Grieve, R. A. F., and Cintala, M. J., *Icarus*, 114, 68-79, 1995; [7] Izenberg, N. R., *et al.*, *GRL*, 21, 289-292, 1994; [8] Sharpton, V. L., in *Large Meteorite Impacts and Planetary Evolution: GSA special paper 293*, 19-27, 1994; [9] Weitz, C. M., *et al.*, *LPSC XXV*, 1483-1484, 1994; [10] Campbell, D. B., *et al.*, *JGR*, 97, 16,249-16,277, 1992.