# VENUSIAN CRATERS AND THE ORIGIN OF CORONAE.

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**Introduction:** Discussion of the geological evolution of Venus generally assumes that the planet underwent widespread, if not complete, resurfacing by volcanism about 500 Myr ago. In the absence of active plate tectonics - so the argument runs - Venus is heating up [1], although some heat is being lost from the interior by conduction through the crust and, more importantly, through several hundred diapiric structures which are manifested at the surface by the circular-to-oval structures 100-2600 km in diameter, known as coronae [2].

The present study suggests that many coronae are impact craters and argues that the wide range of morphologies displayed by the combined population of coronae and acknowledged craters is due to variations over time in the nature of the target material and of the venusian atmosphere. The key implication is that Venus did not undergo resurfacing ~ 500 Myr ago and, in the absence of plate tectonics, that it now loses heat primarily by conduction through the crust and along rifts. In short, the Venusian greenhouse has underfloor heating.

**Data**: Early investigators interpreted some coronae as ancient impact craters which had been deformed by endogenous processes or were in some way degraded [3]; it was also suggested [4] that coronae represented volcanism that had been triggered by impacts. The resurfacing thesis arose from the finding that Venus displays few obviously recognisable impact craters, that they are little deformed, and that their distribution is very uniform [5]. Crater-counts gave an age for much of the planet of 300-700 Myr, and the time taken for resurfacing as 10-100 Myr [6]. Resurfacing has recently been questioned [7] following reassessment of the directional model of venusian evolution and of the distribution of impact craters.

The corona-count of 362 in the original survey [2] was based on Magellan imagery covering > 90% of the planet. Altimetric data and USGS synthetic stereoscopic images then revealed a large number of additional coronae which were difficult to detect on SAR imagery, largely because they lacked a fracture annulus [8]. Addition of the 106 new coronae gives 54% to groups 4, 6, 7 and 8; that is to say, over half the coronae have the same cross-sectional form as unaltered or flooded impact craters on the Moon or other planetary. Extending the comparison to impact craters with central peaks by adding coronae of group 3 would increase the proportion to over 67%. Put another way, after allowing for the 14% nondescript coronae of group 9 [9], only 19% of coronae would be out of a place in a catalogue of lunar impact craters if judged by their cross-sectional form. Even then, Gosses Bluff, in the Northern Territory of Australia shows that differential erosion can invert crater morphology by selectively removing material outside the crater rim to leave the crater and its contents standing above the surrounding plain in the style of corona groups 2 and 3a.

Venusian impact craters are usually identified by having sharp rims bordered by asymmetrical radar-bright ejecta blankets, whereas typical coronae lack both. The larger impact craters, such as Mead or Cleopatra (d = 100 km), lack central peaks and, like their lunar counterparts, have multiple rims. Many comparable coronae of size range $d \sim$ 125-870 km [2] display a concentric double ring. The survival of ejecta blankets is of course a matter of the prevailing erosional regime: no subaerial crater on Earth has yet been found to display such a flamboyant feature, even when allowance is made for the highlighting produced by SAR imaging. This is presumably because weathering and erosion would soon obscure any such feature. Some ejecta degradation by weathering and wind has been detected on Venus. In any case, the observation that impact craters are all in pristine condition [10] is self-fulfilling, because degraded craters are then discounted as potential impact features.

Most impact craters have been surrounded and partially filled by postimpact lavas [11]. This has had the effect of reducing their apparent depth, creating dark floors, and partially burying any ejecta. Many coronae are likewise associated with volcanicity, both in their interiors and on their flanks [2]. As on Earth, departures from circularity which are not due to embayment or breaching by flows could reflect faulting, jointing, and other planes of weakness.

**Statistics**: A lognormal frequency distribution is a very good model for the distribution of both corona types. A two-sided Kolmogorov-Smirnov test [12] confirms that there is no statistically significant difference between the cumulative distributions for the Type 1 and Type 2 coronae ($n_1$=407, $n_2$=107, $D_n$=0.055; this is very much smaller than the critical value of the Kolmogorov-Smirnov statistic at the 0.01 level of significance, $D_{84.72,\ 0.01}$= 0.19; the $p$-value for the maximum observed difference, $D_n$=0.055, is greater than 0.99).

Although the median area of the population of impacts is much smaller than that of the coronae, the spread of the lognormal distributions of coronal and impact areas is very similar.

Coronae are randomly distributed in the plains and display strong clustering elsewhere [2], notably in middle elevations and near chasmata or rifts [13]. Impact craters are randomly distributed throughout the planet, albeit with the slight clustering inevitable with stochastic processes [5], but, if the two populations are combined, few areas are blank, clustering is blurred, and there is no obvious correlation of numbers with altitude. Although the distribution of the coronae with latitude reflects a spatial clumping, similar apparent weak agglomeration occurs for 1562 lunar impacts.

Like other processes [7], corona formation is not confined to any particular phase in the planet's evolution. There is no correlation between stratigraphic age, insofar as this can be identified from the available imagery, and corona morphology [8]. It is of course not always possible to distinguish between the age of a rock unit and the age of the proposed structure: the Barringer Crater in Arizona is found in Cretaceous rocks. However, a detailed analysis of the Scarpellini (V33) quadrangle of the V Map at 1/5M [8] showed that 62% of all the coronae in that quadrangle were found on the youngest materials ('regional plains') and only 3% on tessera. The last is probably an underestimate because, whether or not tessera terrain is generally ancient, it is characterized by intense deformation including episodes of extension and compression, but the observation runs counter to any assumption that coronae reflect long-lived deep sources. Four of the corona types identified earlier as consistent with an impact origin (3, 4, 6 and 7) are found in various terrains; type 8 (basins) are concentrated in regional and lineated (i.e. tectonised) plains [8]. Basins are considered to represent the earliest manifestation of plume development but could be simple craters or complex craters which have been buried by later material. In addition to overlapping the upper end of the size distribution of impact craters, coronae fall well within the possible magnitudes of the rings encountered in the development of multi-ring basins on Mars, Mercury and the Moon, which are generally agreed to be of impact origin.

The effect of an impact owes much to its timing and to the atmospheric history of the target. There is good isotopic evidence for the equivalent in water to 0.12% of a full terrestrial ocean formerly on Venus [14], and some of the canali of Venus may have been cut by running water [15]. A plausible explanation for the loss of the water is early outgassing 'during the first billion years and associated with intensive impacts' [16]. Some early craters may thus have formed in regolith containing moisture, and, as near-surface temperatures were lower than the present ~740K, the basalts that dominate the Venusian surface would have been somewhat less ductile and more retentive of small craters. Repeated climate changes, to which small-strain deformation features have been ascribed [17], would doubtless complicate crater morphologies.

At the very least, earlier times will have been characterised by a thinner atmosphere; the runaway greenhouse that is widely held responsible for the buildup of $CO_2$ was cumulative, even if rapid, and thus initially ineffective; smaller impactors would have found it easier to reach the planet's surface than under current circumstances. It follows that parts of the Venusian surface are much older than generally accepted and, consequently, that they embody a long history of geological and climatic change. Mismatches between the topography and the measurable geophysical properties of Venus would seem inevitable.

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