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The coronae of Venus: Impact, plume, or other origin?

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ABSTRACT

The surface of Venus hosts hundreds of circular to elongate features, ranging from 60 to 2600 km, and averaging somewhat over 200 km, in diameter. These enigmatic structures have been termed "coronae" and attributed to either tectonovolcanic or impact-related mechanisms. A quantitative analysis of symmetry and topography is applied to coronae and similarly sized craters to evaluate the hypothesized impact origin of these features. Based on the morphology and global distribution of coronae, as well as crater density within and near coronae, we reject the impact origin for most coronae. The high level of modification of craters within coronae supports their tectonic nature. The relatively young Beta-Atla-Themis region has a high coronal concentration, and within this region individual coronae are closely associated with the chasmata system. Models for coronae as diapirs show evolution through a sequence of stages, starting with uplift, followed by volcanism and development of annuli, and ending with collapse. With the assumption of this model, a classification of coronae is developed based merely on their interior topography. This classification yields corona types corresponding to stages that have a systematic variation of characteristics. We find that younger coronae tend toward being larger, more eccentric, and flatter than older ones, and generally occur at higher geoid and topography levels.

Keywords: Venus, coronae, impact craters, volcanism, tectonism

INTRODUCTION

Of the terrestrial planets, Venus most resembles Earth, but with key differences. The two planets have similar size, density, and surface basalt composition; however, Venus, unlike Earth, undergoes retrograde rotation, has no magnetic field, lacks water, and has a very dense atmosphere. Although Venus does not display Earthlike plate tectonics, it does show evidence of both volcanic and tectonic activity. Here we will argue that numerous large circular features on Venus, called coronae, are a manifestation of these processes.

Venus's surface hosts nearly 1000 unambiguous impact craters, ranging in diameter from 1.5 to 280 km. The planetary crater density has been used to infer a relatively young surface age for Venus, in the range of 750–300 Ma (Phillips et al., 1992; Schaber et al., 1992). A more recent estimate (McKinnon et al., 1997) widens that range, to 1000–300 Ma. To a first order, the crater distribution approximates a random distribution (Phillips et al., 1992); however, terranes may differ in crater density (Ivanov and Basilevsky, 1993; Price et al., 1996). More specifically, a slight deficit, of about twenty craters, has been documented, statistically, near Venus's chasmata (Stefanick and Jurdy,

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1996). The majority of the craters appear pristine in radar images, although slightly fewer than two hundred display clear modification by either volcanic or tectonic activity or both. Craters, when viewed at the highest available resolution, however, often reveal evidence of subtle modification (Herrick, 2006). In addition, some craters show enigmatic, parabolic halos: impact-related phenomena unique to Venus. These parabolic halo-associated craters preserve impact debris that has settled in the presence of zonal winds and may represent the most recent 10% of Venus's history (Basilevsky and Head, 2002).

Veneras 15 and 16 mapped Venus's surface with radar that Barsukov et al. (1986) used to identify ringlike, uplifted features, named "coronae" or "ovoids." Pronin and Stofan (1990), using corona morphology, further classified 32 features that had been identified on ~20% of the planet, as imaged by Venera radar. With the Magellan probe's improved resolution and radar coverage exceeding 90%, Stofan et al. (1992) were able to catalogue and characterize 362 structures that have an "annulus of concentric tectonic features." These coronae and coronalike features were classified according to morphology; individual features ranged from 60 to 2000+ km in diameter, and many of them displayed circular to elliptical annuli and raised interiors.

Coronae on Venus have been attributed to a variety of mechanisms. When coronae were first identified on Venus's surface, they were considered "volcano-tectonic" features because of associated deformation and lava flows (Barsukov et al., 1986). However, in noting five hundred additional circular features of "unclear origin," the authors speculated whether these could have resulted from the "reworking" of ancient impact basins (Barsukov et al., 1986). In their analysis of Venera data, however, Pronin and Stofan (1990) selected twenty-one features for which they identify corona characteristics. From these examples they documented an evolutionary sequence for coronae with initial uplift and volcanism and later annulus development. On the basis of raised topography and associated volcanism, coronae were attributed to diapirs or hotspots, and their clustering and location at tectonic sites further suggested that coronae were related to Venus's global tectonics.

Noting, from Magellan images, the nonrandom distribution of coronae and the age progression for overlapping coronae, Stofan et al. (1992) attributed coronae to the effects of mantle plumes beneath a stationary venusian surface. Later, Stofan and Smrekar (2005) attributed Venus's large topographic rises ("regiones") to mantle plumes. They inferred multiple scales of upwelling on Venus, with coronae operating at an intermediate scale between volcanoes and larger volcanic rises. Furthermore, Stofan and Smrekar (2005) postulated that due to the lack of plate tectonics, Venus may release heat via a larger number of secondary upwellings, coming from a shallower level, which generate plumes. Koch and Manga (1996) replicated the raised rims of coronae with a model for a rising diapir that spreads at the level where it reaches neutral buoyancy. Based on the diapir model, DeLaughter and Jurdy (1999) reclassified coronae according to the extent of interior uplift of each structure, which they interpreted as a measure of stage, or degree of maturity, of individual features. Noting the selective location of coronae, Johnson and Richards (2003) argued that coronae could be due to small-scale transient effects coexisting with larger-scale upwellings, such as those that produce major highland provinces. A more complete history and description of the variety of proposed models for coronae formation are provided by Herrick et al. (2005).

Recently, Venus's coronae have once again been interpreted as impact-related. Vita-Finzi et al. (2005) analyzed an expanded database of 514 coronae, of which 362 had been catalogued by Stofan et al. (1992); the remainder, which they termed "stealth" coronae, were features with incomplete annuli from the catalogue of Tapper et al. (1998). Based on comparison of the morphology and distribution of Venus's coronae with those of lunar craters, Vita-Finzi et al. (2005) argued that coronae are impact features and that the variation in corona form results from the location of the impact and subsequent modification. Hamilton (2005) asserted that, on Venus, a gradation exists between pristine, generally accepted craters and much older, highly deformed features, and that circular features classified as coronae are in fact the consequence of ancient impacts. As noted in both these studies, a reinterpretation of coronae as impact features gives a much-expanded catalogue of craters. This would result in a much older estimate of the age of Venus's surface and bring into question the proposed resurfacing event at ca. 1000–300 Ma. In addition, the identification of Venus's coronae as impact features would require revisiting models for the evolution and heat loss of our sister planet.

In this study, we evaluate a variety of mechanisms that have been proposed to form coronae. Starting with the impact hypothesis, we assess evidence for the age and activity of coronae and compare their distribution with that of known impact craters. We develop and apply a quantitative approach to compare the topographic symmetry of selected, similarly sized features classified as either coronae or craters. Next, we investigate whether the proposed evolutionary model for coronae results in stages that have systematic characteristics, such as size, shape, and dip. We end by proposing a model for coronae that best explains the observations and noting remaining questions.

DATA SETS

The Magellan mission, 1990–1994, provided nearly full coverage of Venus. Because of the thick atmosphere, radar was used, operating in three modes: nadir-directed altimetry, synthetic-aperture-radar (SAR) imaging, and thermal emission radiometry. The altimetry footprint was dependent on direction and latitude, but generally ranged between 10 and 30 km, and the vertical resolution was typically 5–50 m. Over its three cycles, the Magellan radar succeeded in imaging 98% of the planet's surface at high resolution (~100 m), changing the angle of incidence between cycles (Pettengill et al., 1991; Saunders et al., 1991). Consequently, ~10% of the areas were imaged two or three times with different incident angles, allowing very high-resolution topographic analysis using stereo imaging, with op-

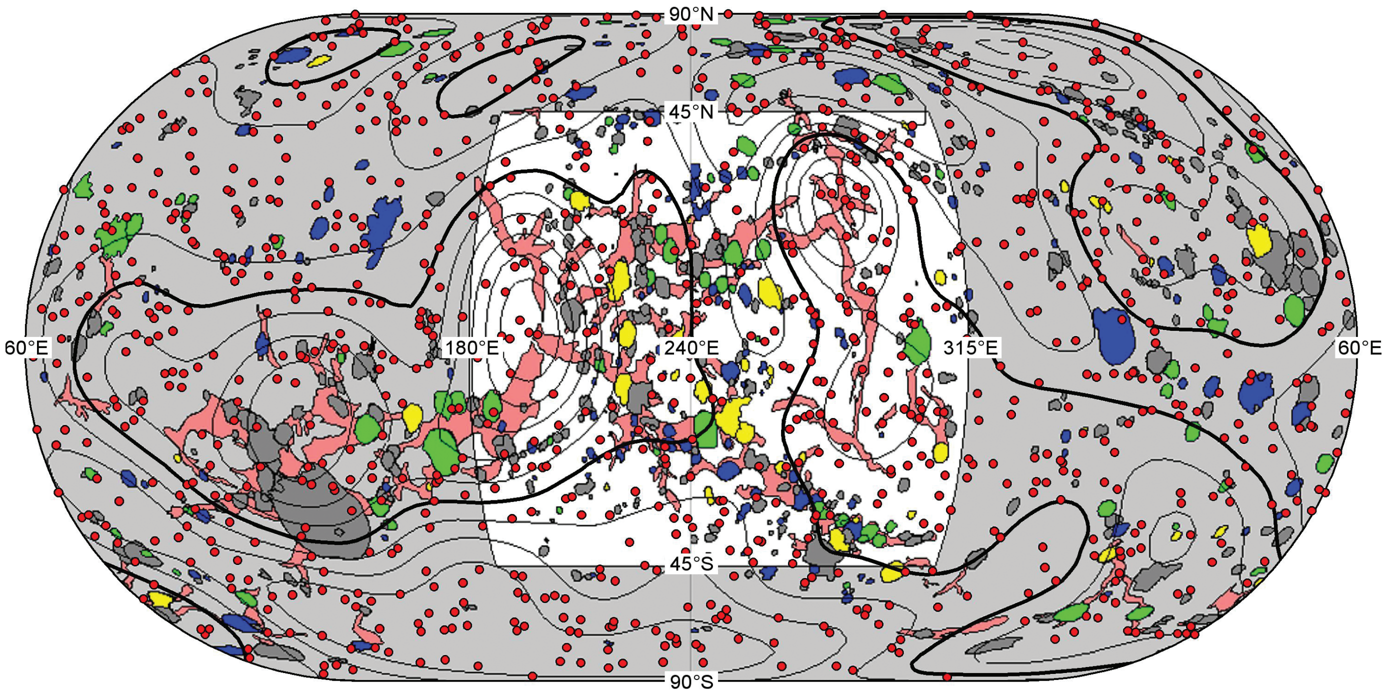

Figure 1. Eckert IV (equal area) projection of Venus's surface, centered on 120°W, showing craters (red dots), chasmata (pink regions), coronae (gray, yellow, green, and blue regions, as defined in the text), and geoid (order 10) 30 m contours. The unshaded area represents the region depicted in Figure 2.

timal lateral resolution exceeding that of the altimetry by a factor of ~100 (Plaut, 1993). The nearly complete coverage provided by Magellan and Pioneer Venus allowed the gravity field, and the corresponding potential field (the geoid), to be determined at a relatively high resolution (order 90) (Sjogren et al., 1997). For our study, we use the geoid field, as well as global altimetry data and the SAR images collected by Magellan.

Classification of coronae remains subjective, as reflected in the numerous published corona catalogues. Herrick et al. (2005), for example, addressed the issue of differentiating volcanoes from coronae, noting the problem that some features are in catalogues of both types. For our analysis we draw our data set from the intersection of the Price and Suppe (1995) and the DeLaughter and Jurdy (1999) catalogues (Fig. 1). Price and Suppe (1995) mapped 669 distinct features as coronae, defined as "circular to irregular volcanic-tectonic features characterized by an annulus of concentric deformation," and ranked according to the increasing proportion of "new volcanic flows" associated with each. A set of 335 coronae that DeLaughter and Jurdy (1999) were able to classify derives from their analysis of a total of 394 features from three sources (Schaber et al., 1992; Stofan et al., 1992; Magee Roberts and Head, 1993). We further discuss this scheme in a later section.

Impact crater distribution and morphology are the primary tools used to analyze planetary surface ages and processes. Here we use the 940-crater catalogue of Phillips and Izenberg (personal commun., 1994; Phillips et al., 1992), as shown in Figure 1. As previously mentioned, these craters have a first-order random global distribution, indicating a nearly uniform surface age for Venus. More detailed analysis (Price and Suppe, 1995) suggested a terrane-based density structure, with plains the most heavily cratered (and thus oldest) terrane. Morphologically, Phillips et al. (1992), using radar imagery, identified the minority of craters that have been obviously modified: 158 tectonized and 55 embayed, with 19 craters showing clear evidence of being both tectonized and embayed. However, close analysis of craters at very high resolution (<100 m), made possible with stereo imaging, reveals tectonic and volcanic activity for numerous craters, suggesting that perhaps most of the craters have been modified (Herrick and Sharpton, 2000; Herrick, 2006). Both studies thus concluded that volcanic activity on Venus may be more widespread than initially believed. It is important to remember, however, that stereo imaging is possible for only a small percentage of the surface, so any such studies are necessarily very limited in their scope. For example, in their study of the Beta-Atla-Themis region, Matias and Jurdy (2005) found only 13 out of 153 craters with the necessary double coverage and only two with triple; thus in that region fewer than 10% of the craters are candidates for stereo imaging. We use the global crater data set of Phillips and Izenberg in our analyses, as well as their assessment of modification. We argue that those craters obviously modified, as judged directly from radar images, have suffered more significant alteration than the subtle modifications that can be discerned only with stereo imaging, and thus are more indicative of major alteration processes.

Like the Earth, Venus has a global rift system. The 1978

Pioneer missions to Venus provided radar and gravity data that enabled Schaber (1982) to identify a global system of extensional features on Venus, which he cited as evidence of tectonic activity, despite the apparent lack of Earth-style plate tectonics. Schaber attributed the extension to upwelling-related processes, such as at Earth's continental rift zones, but noted the global scope of these extension zones, similar in scale to Earth's mid-ocean ridge system. These rift zones can be fit by four great circle arcs (Schaber, 1982). Using the nearly global coverage provided by Magellan, Solomon et al. (1992) characterized these rift zones, termed "chasmata," as rugged regions with some of Venus's deepest troughs, extending thousands of kilometers. They noted the extreme relief, with elevation changing as much as 7 km in just 30 km distance. The 54,464-km-long Venus chasmata system, as defined in greater detail by Magellan, can be fit by great circle arcs at the 89.6% level, and when corrected for the smaller size of the planet, the total length of the chasmata system measures (Jurdy and Stefanick, 1999) within 2.7% of the 59,200 km length of the spreading ridges determined for Earth by Parsons (1981). The chasmata with the greatest relief on Venus experienced linear rifting during the latest stage of tectonic deformation (Head and Basilevsky, 1998). The chasmata shown in Figure 1 were derived from mapping by Price and Suppe (1995). The geoid of Venus, as determined from Magellan data, is superposed on the other features in Figure 1. We display a smooth geoid field (order 10), similar in scale to the features of interest.

Venus's regiones, broad areas of relief, number around ten. Stofan and Smrekar (2005) noted that regiones range in diameter from 1000 to 2700 km, rise between 0.5 and 2.5 km above the surrounding terranes, and have positive gravity anomalies. A regio might be dominated by rifts, as are Atla and Beta, discussed here (Fig. 2), or by volcanism, as are Imdr, Bell, and

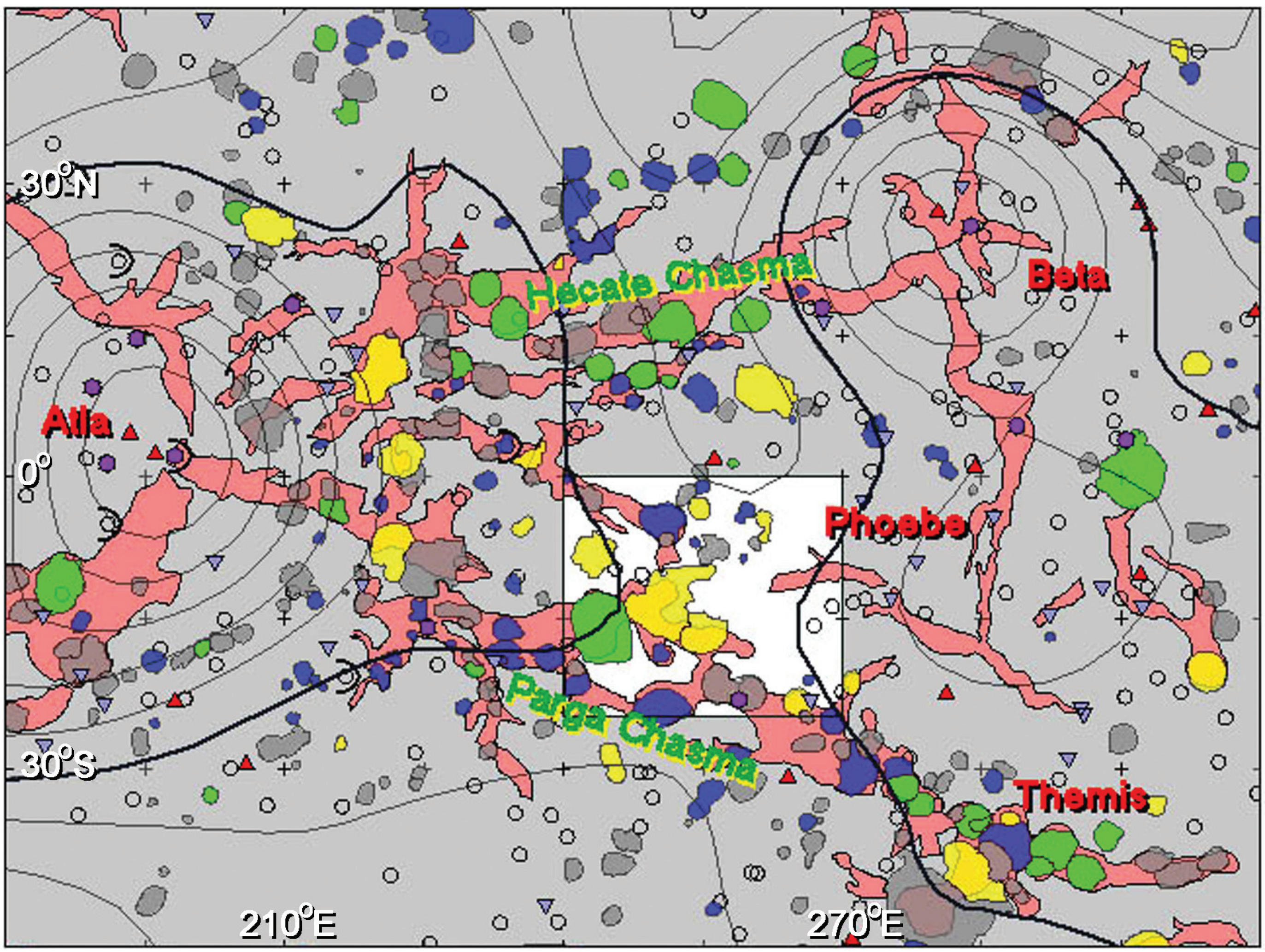

Figure 2. The "BAT" region—the area between Beta, Atla, and Themis regiones. Pink—chasmata; yellow—domal coronae; green—circular coronae; blue—calderic coronae (classifications from DeLaughter and Jurdy, 1999). Dark gray—unclassified coronae; open circles—pristine craters; red upward-pointing triangles—embayed craters; light blue downward-pointing triangles—tectonized craters; purple circles—craters that have been both tectonized and embayed. Craters with dark halos are indicated by black arcs. Contour lines are for geoid (order 10) 30 m contours. The unshaded area is shown in detail in Figure 4.

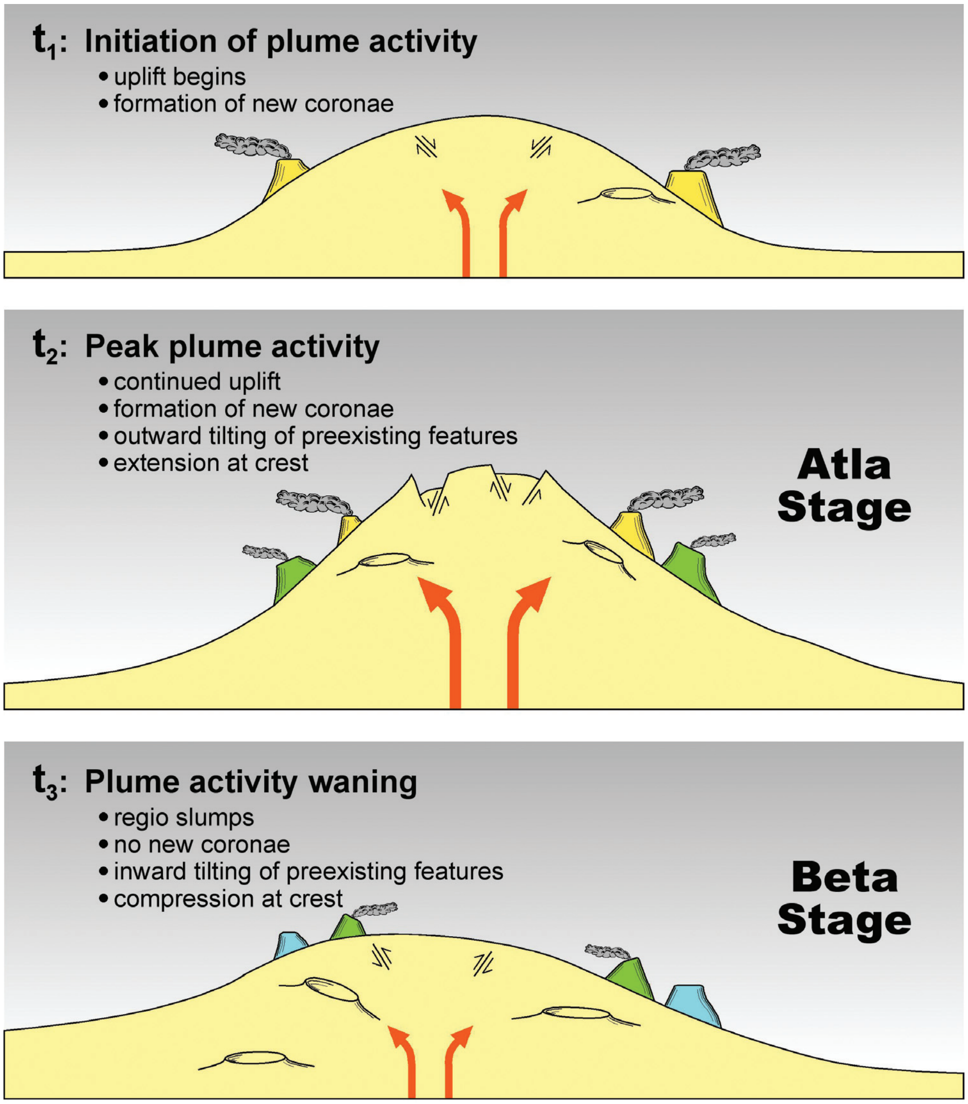

Figure 3. Model for the evolution of regio features, such as Atla and Beta.

Dionne, or be dominated by coronae, as is Themis (Stofan and Smrekar, 2005). The rift-dominated regiones, Atla and Beta, have the greatest topographic expression. Atla and Beta are the sites of several rift intersections and the two major geoid highs on Venus. Curiously, the geoid "bulls' eyes" also coincide with the intersections of arcs fitting the chasmata. The current deformation of Venus's surface has been described as being caused by a swell-push force, the result of a steep gradient of the geoid height (Sandwell et al., 1997). Thus, these areas may be experiencing the most intense deformation on the planet, and the network of rifts may have formed in response to this deformation.

Coronae occur in many rift segments, yet none actually occurs at these intersection points. Perhaps just as remarkable, Atla has a partial ring of four domal coronae, all between four and five geoid contours from the crest, while Beta has a partial ring of six or so calderic coronae between three and four contours from its crest. Possibly, thicker crust at the regiones inhibits the formation of coronae in association with chasmata (Bleamaster and Hansen, 2004). On the other hand, using geoid-topography ratios, models for these highlands suggest thinning of a thick lithosphere (150–350 km) to as little as 100 km over an anomalously hot (by as much as 400–1000K) asthenosphere (Moore and Schubert, 1997). Such an analysis (which requires wavelengths greater than 600 km) is not appropriate for coronae, unfortunately, given their smaller size as well as their close proximity to each other. The observed distribution of coronae relative to the regiones led Stoddard and Jurdy (2003) to hypothesize that Atla represents a younger phase of large-scale upwelling than Beta (Fig. 3). Craters, initially formed flat, show some tilting around Atla and Beta (Jurdy et al., 2003; Matias et al. , 2004) consistent with an active uplift of Atla and a recent slumping of Beta. Additionally, coronae often intertwine with chasmata or are contained by the chasmata walls (Fig. 4).

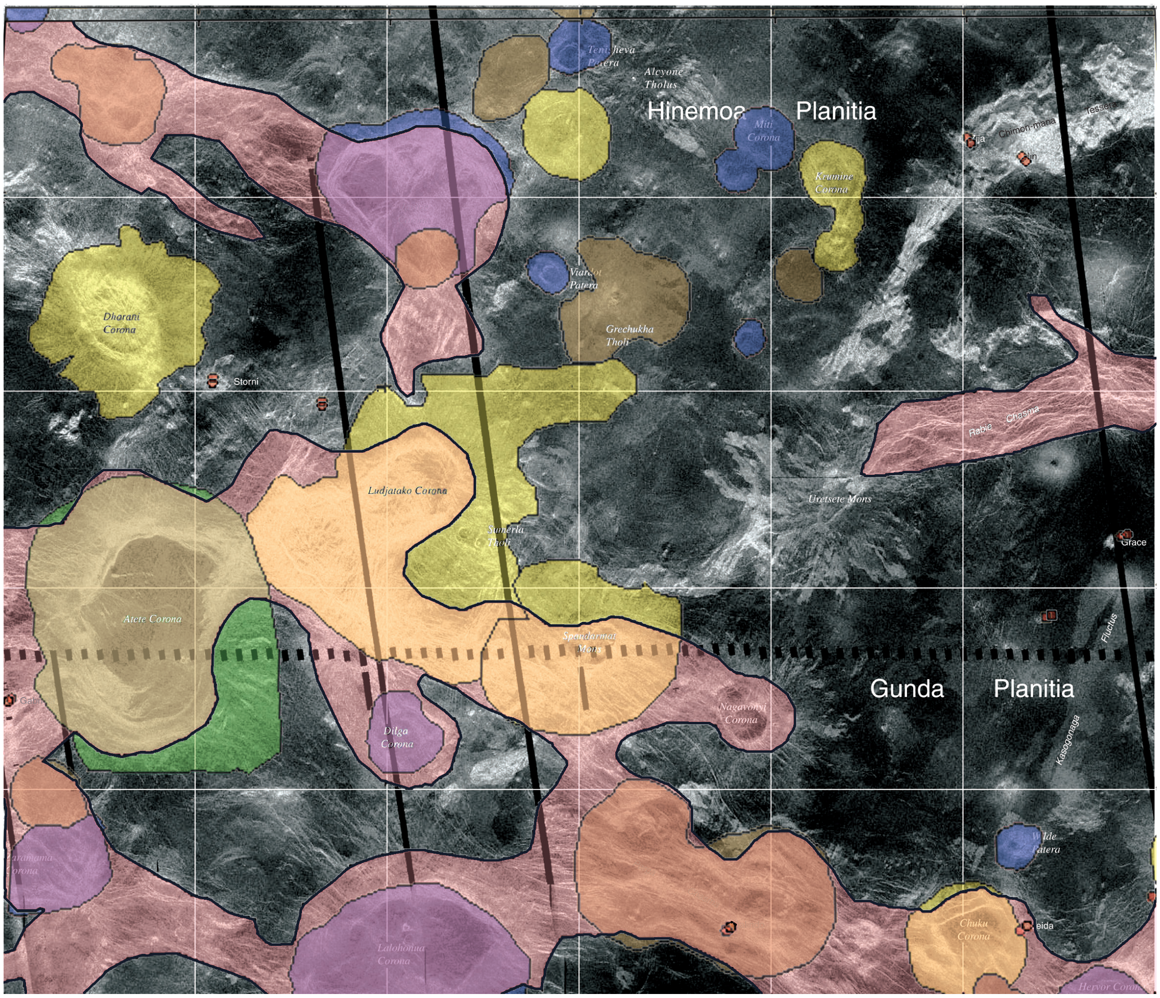

Figure 4. Detail of Parga chasm exemplifying the intertwining relationship between many coronae (yellow, green, blue, green, and gray) and chasmata (pink). The region extends from 240°E to 270°E, 0°S to 25°S. 5° grid. The radar image is from http://planetarynames.wr.usgs.gov/images/v40_comp.pdf.

TESTING THE IMPACT ORIGIN HYPOTHESIS

Crater Statistics

An ancient impact origin for coronae, as opposed to recent endogenic activity, makes several testable predictions. If, as suggested by Hamilton (2005, 2007) and Vita-Finzi et al. (2005), coronae are ancient impact features, with ages of up to 3.9 Ga, they should be significantly more heavily cratered than the younger, average-aged surface. Previously, Namiki and Solomon (1994) evaluated impact crater density within coronae interiors, finding evidence for significantly lower densities within late-stage coronae, which they defined as being dominated by volcanism. Price and Suppe (1995) evaluated crater density on various terranes and found that coronae, as a terrane type, have low crater densities. Using the corona data set of Stofan et al. (1992), DeLaughter and Jurdy (1997) found low crater density out to four corona radii near the uplifted coronae, whereas the density was about normal for those coronae with collapsed interiors. In our analysis, we found that although the 669 coronae from the map of Price and Suppe (1995) occupy 10.6% of Venus's surface, they host only 7.0% (66 of 940) of the crater population (Table 1), suggesting that the coronae are, as a whole, younger than the average surface age. On the other hand, an excess (again, when compared to surface area) of Phillips et al.'s (1992) unambiguously tectonized craters (24, or 15.2%, of 158 total) are found within coronae, indicating that coronae are more tectonically active than the average surface region. Somewhat surprisingly, embayed craters are under-represented within coronae (5.5% of the planetary population on 10.6% of the planet's surface). Of course, with smaller populations, interpretations from these statistics become less certain. For a random distribution, the standard deviation is the square root of the number counted (Fisher, 1973, sect. 15). Thus, for a count of 4 items, one standard deviation would include counts of 2–6 (4 ± 2). Obviously, for such small sets, it would not be possible to achieve counts that

TABLE 1. CRATER DENSITY IN CORONAE, RIFTS, AND THE BAT REGION

			Craters on feature type		Tectonized craters on feature type		Embayed craters on feature type		Tectonized (T) and embayed (E) craters on feature type	
	Number of features	Coverage (% of Venus's surface area)	No.	Percent of total craters	No.	Percent of tectonized craters	No.	Percent of embayed craters	No.	Percent of T and E craters
All coronae	669	10.6	66	7.0	24	15.2	3	5.5	2	10.5
Domal (Y)	39	0.9	3	0.3	1	0.6	0	0.0	0	0.0
Circular (G)	83	2.0	14	1.5	5	3.2	1	1.8	1	5.3
Calderic (B)	164	2.2	15	1.6	5	3.2	0	0.0	0	0.0
Rift segments	57	8.3	59	6.3	32	20.3	8	14.5	7	36.8
BAT region	1	26.5	224	23.9	44	27.8	27	49.1	11	57.9

Notes: "BAT" region—the area between Beta, Atla, and Themis regiones; number of features—total number of each feature on Venus's surface; coverage—total percentage of Venus's surface area covered by each type of feature. For crater columns, the total number of craters found on each type of feature is given, as well as the percentage of the total number of that type of crater found on Venus. For example, 24 tectonized craters were found on all coronae, which represents 15.2% of the 158 tectonized craters found on Venus.

deviate enough from the average to achieve two full standard deviations.

Another consequence of the impact origin hypothesis is that coronae, as ancient impact sites, should be concentrated on the oldest areas of the planet's surface. However, we claim that the opposite is true, that coronae are actually concentrated in the youngest region of Venus's surface. Coronae are most heavily concentrated in the so-called BAT region, the area between Atla, Beta, and Themis regiones (Fig. 2). We define this region roughly as between 45°N and 45°S, 180°E and 315°E. Using these boundaries, we find that 292 (43.6%) of all coronae lie within the BAT region, which itself comprises only 26.4% of the planet's surface. Unambiguous BAT region impact craters total 224 (23.9%), but if we assume that coronae are additional impact sites, 32% of all impact features are found here, which then indicates a somewhat older than average surface age. However, by most accounts the BAT region represents the youngest, most active region on Venus (e.g., Head and Basilevsky, 1998).

Several lines of evidence support this claim. Examining the set of young, commonly agreed-upon craters shows that the BAT region is somewhat deficient, arguing for a younger, not older, region. Also, the BAT region contains nearly two-thirds (by area) of all rifts as identified by Price and Suppe (1995). In their global sequence of tectonic deformation, Head and Basilevsky (1998) found that linear rifting prevailed in the latest stage of events. That rifts are among the most active (or most recently active) features on Venus can be further demonstrated by their relative dearth of craters and the plethora of tectonized and embayed craters (Table 1). Crater Uvaysi (2.3°N, 198.2°E) provides additional support of our conclusion that the BAT region has experienced very recent activity. This crater, at the intersection of three chasmata and nearly at Atla Regio's crest, has been classified as both tectonized and embayed. Opportunely, the clear evidence of modification is coupled with the presence of a radar-dark parabola with Uvaysi, near the apex of Atla Regio. As argued by Matias and Jurdy (2005), these two occurrences constrain the volcanism and tectonism of the crater as recent, because parabolic haloes remain from only the last 10% of Venus's surface history. Uvaysi is one of eleven of the planet's nineteen craters both tectonized and embayed (nearly 60%) contained within the BAT region. This nearly 60% measures more than double what would be expected based solely on area. Looking at cratering and stratigraphy, Vezolainen et al. (2004) suggested that Beta uplift began after the average age of the surface (T) and has continued until after 0.5 T. Basilevsky and Head (2007), on the basis of stratigraphic relations to neighboring terranes, also suggested recent or current uplift of Beta Regio. Taken in its entirety, the BAT region itself also shows the relative lack of craters and the excess of modified craters seen by the rifts. Furthermore, the two largest geoid highs coincident with Atla and Beta regiones may indicate a dynamic nature for these features, and thus provide additional support for a young age for the BAT region.

Coronae, if they indeed are the results of ancient impacts, should predate active rifts. Coronae and chasmata, however, are intimately related, as can be seen in Figure 2. Even a cursory inspection of Hecate and Parga chasmata (extending between Atla and Beta and between Atla and Themis, respectively), depicted in Figures 2 and 4, shows this relation. In many cases, corona boundaries seem constrained by the rift walls (Fig. 4). A more quantitative analysis of corona and rift orientation was also undertaken (Stoddard and Jurdy, 2004). This comparison shows that although there is no apparent relation for coronae outside rifts, coronae within rifts tend to parallel the rift axis (Fig. 5). Given their locations and orientations, we argue that coronae within rifts must develop as part of the rifting process and/or continue forming postrifting. If, on the other hand, coronae were ancient, predating the rifts, we would find them not in the rifts, but bisected by the rifts. On the basis of the previous analyses, we here conclude that coronae cannot be due to ancient impacts.

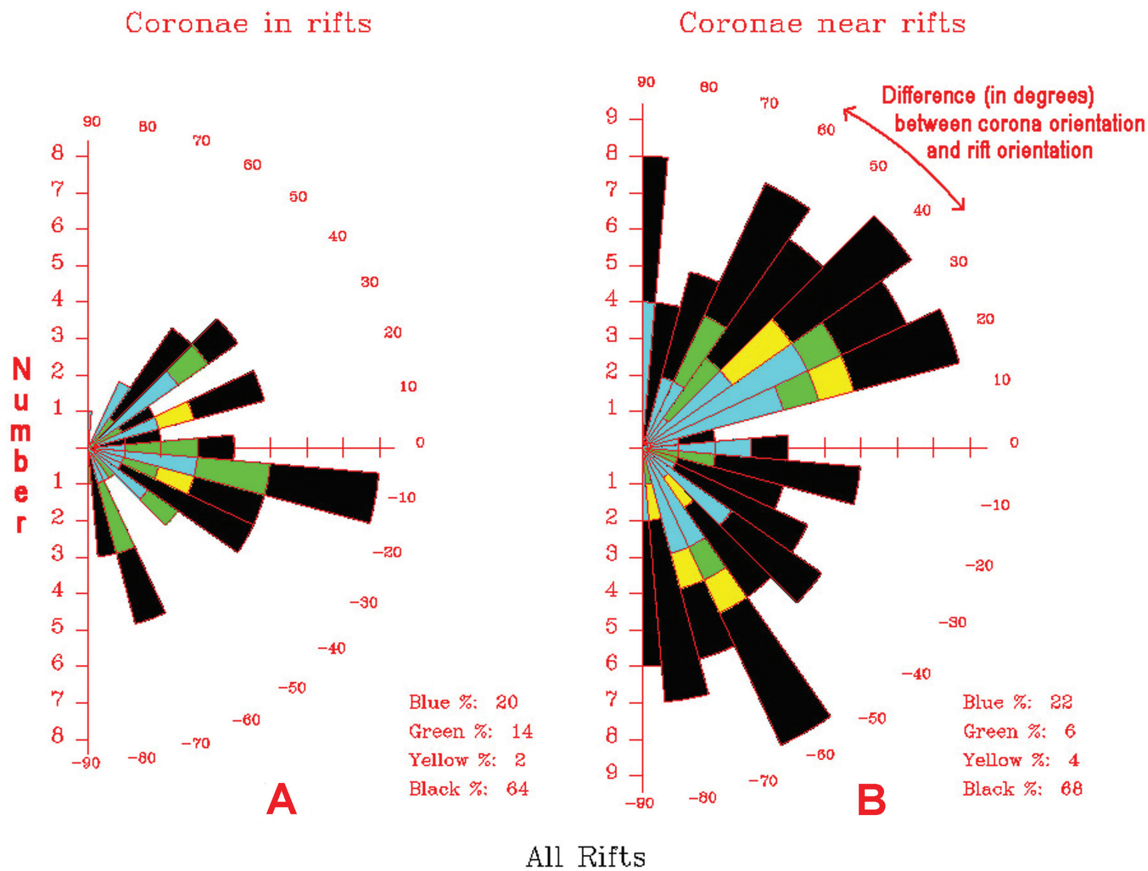

Figure 5. Corona orientation relative to rifts. The orientation of the long axis of the best-fitting ellipse to each corona is compared to the orientation of the nearest rift segment. (A) For coronae within the central rift graben, there is a preferred corona orientation subparallel to the rift axis. (B) Coronae near, but not in, rifts do not show this behavior. Color scheme (yellow, green, blue) matches the classification scheme (domal, circular, calderic, respectively) of DeLaughter and Jurdy (1999).

A model of coronae as ancient impacts needs to address the lack of cratering between the hypothesized ancient corona impacts and young crater impacts and the lack of transitional features between coronae and craters. In positing an old "impact age" for coronae, neither Hamilton (2005) nor Vita-Finzi et al. (2005) addressed in detail transitional craters, i.e., those younger than ancient "corona" impacts but older than the more commonly accepted impact set. The size distributions of craters and coronae (Fig. 6 *in* Vita-Finzi et al., 2005) clearly show two well-defined and distinct populations.

Spatial distribution has been proposed as a means for determining the origin of coronae. Vita-Finzi et al. (2005), in their argument for an impact origin for coronae, claimed that the corona distribution on Venus resembles global impact distributions on both Venus and the Moon. We challenge their conclusion on two grounds. First, we assert that the lunar comparison is flawed, because the catalogue of 1562 lunar craters used, while the best currently available, consists of named features only, and thus has a strong near-side bias, as well as a bias against high-latitude features (Deborah Lee Soltesz, USGS, 2006, personal commun.). Correspondingly, their lunar "crater density traces," based on that catalogue, peak at 0°N, 0°E (Fig. 10 *in* Vita-Finzi et al., 2005). Second, we observe that the venusian crater distributions were incorrectly displayed by Vita-Finzi et al. (2005). When corrected for decreasing area with latitude, the venusian distribution appears random in both latitude (with the exception of the drop-off toward the south pole due to gaps in satellite coverage) and longitude, unlike the corona distribution (Fig. 6). We therefore argue that the corona distribution on Venus differs significantly from the crater distribution and cannot be used to argue for similar origins. Furthermore, we attribute the complementary distribution of craters and coronae with longitude to crater removal by corona-related volcanotectonic activity.

Quantitative Analysis of Circular Symmetry

Craters by their nature are circular. They are excavated by a roughly hemispherical shock wave, and thus, almost regardless of impact angle, will be round rim-and-basin structures (Melosh, 1989). Underlying structural features, such as faults, and later tectonic deformation can modify crater shape. Perhaps, therefore, the strongest test of an impact origin for coronae is the circularity of these features.

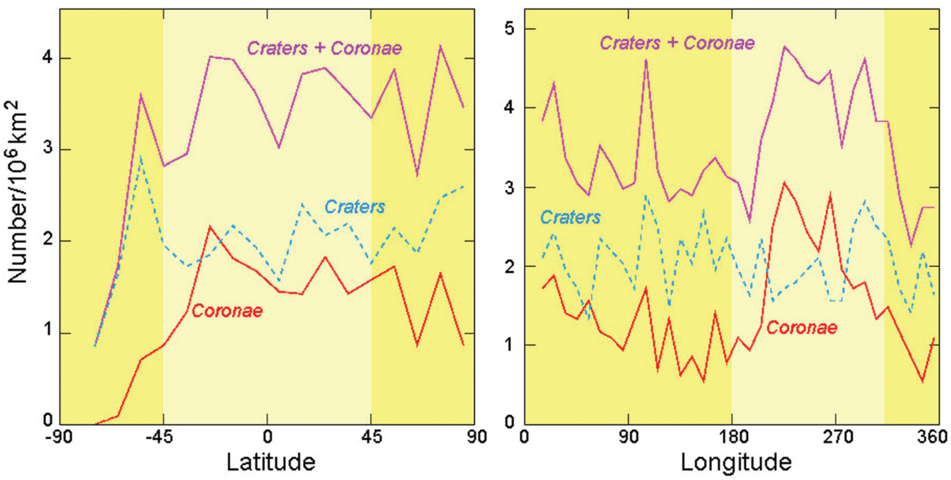

Figure 6. Coronae (red, solid lines), craters (blue, dashed lines), and combined (purple, solid lines) densities with latitude and longitude for Venus (10° bins). The lighter background indicates BAT region limits.

Here we introduce an approach for the assessment of a feature's circular symmetry. Using altimetry data, we compared, by cross-correlation, multiple profiles across a single feature. Jurdy and Stoddard (2005, http://jove.geol.niu.edu/faculty/stoddard/05ChapmanPoster.pdf) provided an example in which Mead crater and two coronae, all measuring ~280 km across, were analyzed. They found that for each corona, profiles cross-correlated at only 25–30% of perfect cross-correlation. Profiles for Mead crater, however, correlated at a much higher level, 80%. Here we report an expanded study for five features generally classified as craters and six whose classification as coronae has been questioned by Hamilton (this volume), the results of which are summarized in Figure 7. We chose only the largest craters, because altimetry data are too coarse to allow enough data points for analyses of smaller features, and also because they are of similar size to the coronae in our study. For each feature, thirty-six profiles (taken every 10°) were extracted from the altimetry data. The average slope was removed from each profile (to nullify the effects of any postemplacement tilting), and the results were aligned and then averaged together. For each feature, each profile was then correlated against the average, and the correlations themselves were averaged to give an assessment of circular symmetry. A perfectly circular feature would have a correlation average of 100%, indicating that each profile was identical to the average profile.

Figure 7A–E shows the results for five craters. Note that for Mead, Cleopatra, Meitner, and Isabella the profiles display the typical rim and basin structure expected for craters, but for Klenova (E) the average profile is more domal, with only a few of the individual profiles looking craterlike. The "contested" coronae are shown in Figure 7F–K. The average profiles for Eurynome (F), Maya (H), and C21 (I) appear craterlike, albeit with more variation among the individual profiles than seen in the generally agreed-upon craters. Anquet (G) has a rim-and-basin structure, but unlike typical craters, has a basin elevated above the surrounding plains. Acrea (K) appears to be a small hill in a large depression, again with a high degree of variation. Ninhursag (J) is clearly domal, and cannot be viewed as a crater.

The variability of the profiles, and thus the circularity of each feature, is summarized in Figure 7L. Those features universally agreed upon as craters (in yellow) have the highest correlation percentages, all at or above 80%, with the exception of Klenova. The disputed features (Fig. 7F–K) are not as circular, although C21 is close. Based on this analysis, we conclude that Klenova has been mischaracterized as an impact crater, and also that C21, a feature previously classified as a corona, may indeed be of impact origin (Table 2). The cases for Maya and Eurynome are more ambiguous. We propose that this type of correlation analysis can be used in an objective assessment of the circularity, and therefore the origin, of the remaining catalogue of similar features.

To address the noncircularity of coronae, Vita-Finzi et al. (2005) and Hamilton (2007) suggested deformation of these features by postimpact tectonic activity. Such activity must be local rather than regional; otherwise, a preferred orientation of the long axes of coronae, reflecting the tectonic stress regime, should be apparent. This is not the case, in relation either to the major tectonic features or to the chasmata (Fig. 5). We have found no correlation between the long axis of individual coronae and their dip direction, as might be expected if coronae were initially circular and their ellipticity and orientation were both related to later deformation.

EVOLUTIONARY MODEL

Here we consider an evolutionary model for coronae, based on rising diapirs, as an alternative to the impact hypothesis. Coronae were assigned to three distinct morphological groups using Magellan altimetry (DeLaughter and Jurdy, 1999). In this classification, *domal* coronae (numbering 54 of the features classified by DeLaughter and Jurdy, 1999) are distinguished by a central uplift with no surrounding moat, and may have associated radial fracturing, often visible only in the SAR images. A flattened interior and an annular moat characterize 93 *circular* coronae; portions of their interiors may be lower than the surrounding plains. *Calderic* coronae, with more than 50% of the

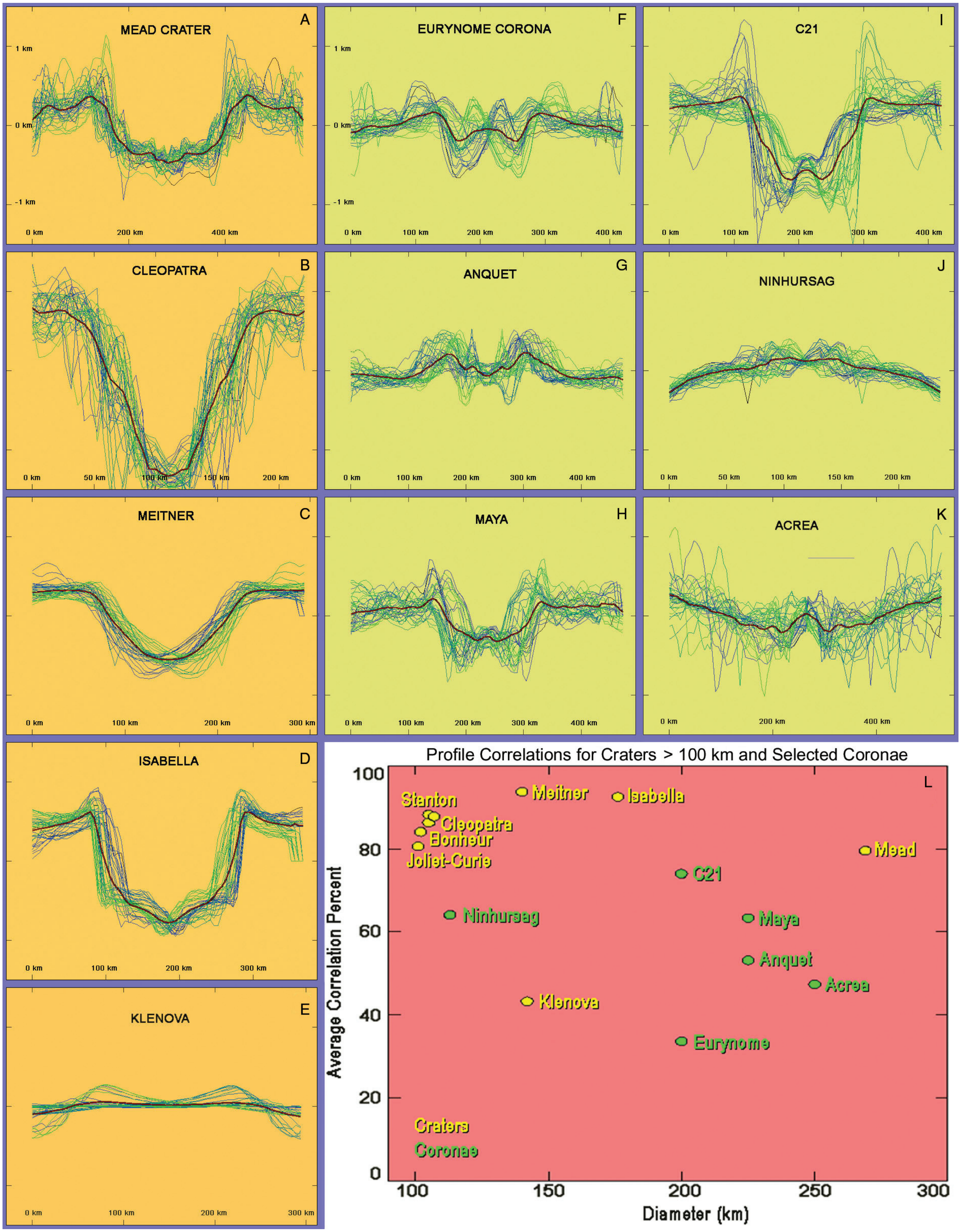
MEAD CRATER
A
1 km
0 km
-1 km
0 km
200 km
400 km
EURYNOME CORONA
F
1 km
0 km
-1 km
0 km
100 km
200 km
300 km
400 km
C21
I
0 km
100 km
200 km
300 km
400 km
CLEOPATRA
B
0 km
50 km
100 km
150 km
200 km
ANQUET
G
0 km
100 km
200 km
300 km
400 km
NINHURSAG
J
0 km
50 km
100 km
150 km
200 km
MEITNER
C
0 km
100 km
200 km
300 km
MAYA
H
0 km
100 km
200 km
300 km
400 km
ACREA
K
0 km
200 km
400 km
ISABELLA
D
0 km
100 km
200 km
300 km
KLENOVA
E
0 km
100 km
200 km
300 km
Profile Correlations for Craters > 100 km and Selected Coronae
L
Average Correlation Percent
Diameter (km)
0
20
40
60
80
100
100
150
200
250
300
Stanton
Meitner
Isabella
Cleopatra
Bonheur
Joliet-Curie
Mead
C21
Ninhursag
Maya
Anquet
Acrea
Klenova
Eurynome
Craters
Coronae

TABLE 2. CHARACTERISTICS OF CRATERS LARGER THAN 100 KM IN DIAMETER AND SELECTED CORONAE

Feature	Latitude (°N)	Longitude (°E)	Diameter (km)	Correlation %	Common classification	New Classification
Joliet-Curie	–1.7	62.4	100.9	81	Crater	Crater
Bonheur	9.7	288.8	102.2	84	Crater	Crater
Cleopatra	65.9	7.0	105.0	86	Crater	Crater
Stanton	–23.2	199.3	107.0	88	Crater	Crater
Meitner	–55.5	321.7	140.0	94	Crater	Crater
Klenova	78.2	104.7	141.9	43	Crater	Corona? (domal)
Isabella	–29.2	204.2	176.0	93	Crater	Crater
Mead	12.5	57.0	268.7	80	Crater	Crater
Ninhursag	–38.0	23.5	113.0	64	Corona	Corona (domal)
C21	29.0	243.0	200.0	74	Corona	Crater
Maya	23.0	98.0	225	63	Corona	Crater?
Eurynome	26.5	94.5	200	34	Corona	Corona? (circular)
Anquet	26.5	98.0	225	53	Corona	Corona (circular)
Acrea	24.0	243.5	250	47	Corona	Corona (calderic)

interior lower than the surrounding plains, constitute the majority (188), and display raised rims and annular moats. The three groups are gradational; consequently, boundaries in this classification are arbitrary. In Figure 8, we show the classification along with radar images of representative coronae corresponding to the stages. The attraction of this scheme is the simplicity of application: one needs to establish only the elevation of the corona interior relative to its surroundings. A further appeal of the approach is the possibility that the three groups may represent evolutionary stages of corona development, from initial diapir uplift to ultimate collapse.

Corona Characteristics by Type

For our analysis of classified coronae, we used the subset of DeLaughter and Jurdy's (1999) catalogue that corresponds to those 669 distinct features mapped by Price and Suppe (1995) as coronae. A total of 287 were matched to the morphologically classified coronae (DeLaughter and Jurdy, 1999). This correlation yielded a smaller set: 39 domal coronae, 83 circular, and 165 calderic, with 382 features remaining unclassified. A more sophisticated scheme could be devised to incorporate more features, but in our study we used this subset.

Next, we investigated the consequences of this classification scheme: Do the three groups of coronae—domal, circular, and calderic—represent stages of corona evolution? If so, an age progression should be evident from the density of impact craters and their modification. As noted, the distribution of impact craters on Venus very nearly approaches random. In Table 1, the crater counts are documented for all coronae, as well as the morphological subgroups. Some intriguing patterns emerge. Coronae cover 10% of the surface of Venus, but contain only 7% of the craters, indicating a younger than average age. Likewise, although domal coronae occupy 0.9% of the total surface area, they contain only 0.3% of the craters; thus the crater density on these coronae is about one-third of what would be expected for average-aged features, and is also less than that for all coronae as a group. Additionally, the circular and calderic coronae have only three-fourths of the number of craters expected for their areas. These crater densities are consistent with the inferred stages, i.e., with the domal the youngest. The circular and calderic coronae, however, have an overpopulation, by 50%, of tectonically modified craters. This analysis (Table 1) shows that coronae, as a set, stand out as younger features, ones with lower crater density. Similarly, Price and Suppe (1995), in their terrane-based study, found that coronae and coronalike features are second only to large volcanoes in having the lowest crater density. Furthermore, our study provides evidence of tectonic modification, as would be expected for the proposed older coronae. In addition, crater densities and modification are consistent with the classification of coronae by evolutionary stage. Alternatively, if coronae were of ancient impact origin, we would expect to find them more heavily cratered, not less, than the average terrane.

Do Coronae Evolve in Size, Shape, and Orientation through Their Lifetime?

If these coronae do, in fact, represent a diapir life cycle, we would expect to see systematic variations in some coronal attributes, such as size, shape, dip, topographic and geoidal

Figure 7. Comparison of topographic profiles across craters and coronae on Venus. For each of panels A through K, thirty-six individual profiles are shown, in blue through green, based on the orientation of the profile. Blue is west-east, proceeding clockwise through south-north, east-west, north-south, and back to west-east. The average profile is depicted by the bold black line. (A–E) Profiles for five craters. (F–K) Profiles for six coronae. (L) Summary of a circularity study for these eleven features plus four others, based on the average correlation among the individual profiles. A 100% average correlation would indicate thirty-six identical profiles and perfect circular symmetry. The features in panels A–E, commonly accepted as craters, are depicted in yellow; green indicates the features in panels F–K, commonly accepted as coronae.

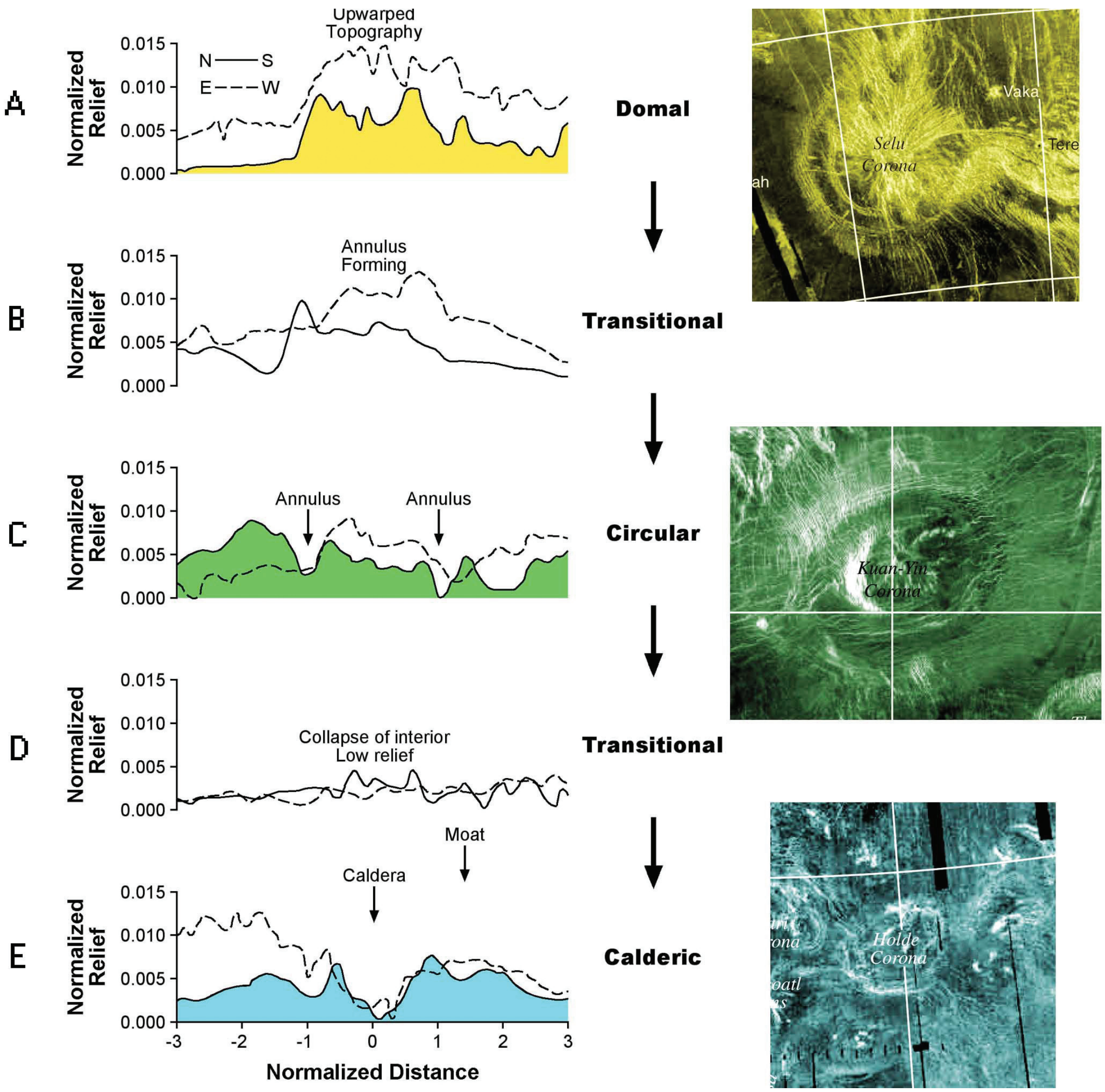

Figure 8. Coronae classification scheme, with example profiles. (A) Domal corona Selu, centered at 42.5°S, 6°E, diameter = 150 km. (B) Domal or circular transitional corona Earhart, 71°N, 136°E, 185.5 km. (C) Circular corona Kuan-Yin, 4.3°S, 10°E, 125 km. (D) Circular or calderic transitional corona Demeter, 55°N, 295°E, 333.5 km. (E) Calderic corona Holde, 53.5°N, 155°E, 100 km. Profiles after DeLaughter and Jurdy (1999). The radar images for Selu, Kuan-Yin, and Holde are from http://planetarynames.wr.usgs.gov/vgrid.html.

elevations, and so on, independent of the morphological criteria by which the coronae were classified. Figure 9A shows length versus dip, and Figure 9B shows the eccentricity versus dip for all coronae, comparing the whole set. The geoid versus topography is shown in Figure 9C. The domal coronae are shown as yellow, the circular as green, and the calderic as blue, with the remaining unclassified ones as black. Although the data show considerable scatter, analysis reveals some interesting patterns.

Quartile analysis provides a useful characterization of the range of values for a set. In quartile analysis the values range from q0 to q4. The lowest fourth of the values range from q0 to q1, the next fourth of the values range from q1 to q2; similarly, the third quarter of the values range from q2 to q3, and the final, top quarter of the values range from q3 to q4. The numbers q1 and q3 are often referred to as the first and third quartiles, and q2 is usually referred to as the median. The numbers q0 and q4 are the minimum and maximum values. For a set with a statistically defined "normal distribution," the quartiles can be related to the standard deviation: For a normal (or Gaussian) distribution, 68.3% of the values lie within one standard deviation of the mean. Alternatively, the range between the first and third quartiles contains 50% of the values, and the points are within 0.675 standard deviation of the mean (Fisher, 1973). We apply this simple, yet informative analysis to the sets of coronae.

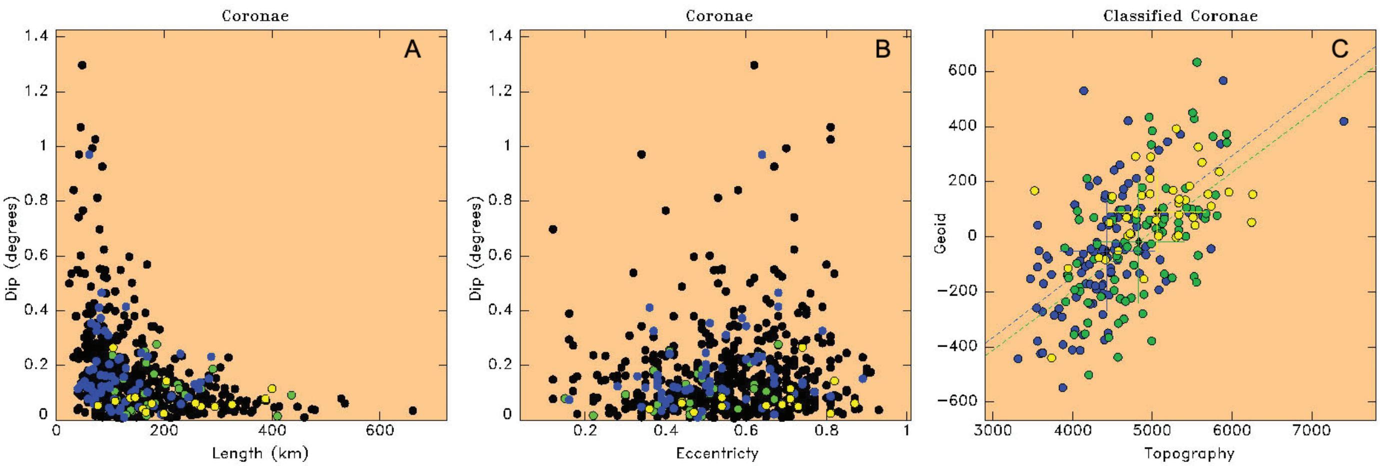

Figure 9. Comparison of various coronal parameters, by corona classification. Yellow—domal coronae; green—circular coronae; blue—calderic coronae; black—unclassified coronae. (A) Length versus dip for coronae. (B) Eccentricity versus dip for coronae. (C) Topography versus geoid; crosshairs indicate average values and standard deviations for each set.

The quartile analysis documents a distinct separation by stage (Table 3). Size strongly depends on the stage: three-fourths of the domal coronae are larger than three-fourths of the calderic ones, with circular coronae intermediate in size. Why are domal coronae (yellow) bigger and more eccentric? Perhaps the initial corona eruption corresponds to an active diapir that later withdraws. The ellipticity is also a function of stage: more than half the circular and calderic coronae have eccentricities of less than 0.50, while more than half the domal ones have eccentricities of over 0.70. A tilt was determined for each feature by determining the dip of a best-fitting plane through the region. The tilt or dip determined for coronae also seems related to the stage: three-fourths of the domal coronae dip less than three-fourths of the calderic, and the circular are intermediate. Although a continuum exists between corona stages, some characteristics distinguish uplifted coronae from largely collapsed ones: the domal coronae are larger, more eccentric, but flatter than the calderic coronae. Systematically, the circular coronae lie between the domal and the calderic for almost all parameters we defined. These patterns further support the morphologic classification of coronae (DeLaughter and Jurdy, 1999) as a simply determined, but useful, indication of stage or degree of maturity of individual features. Thus, the consistent continuum implies an evolutionary sequence, and we infer that the morphology of coronae indicates the stage, with the domal youngest, the circular intermediate, and the calderic the oldest. On the basis of these observations, we suggest that an objectively defined algorithm could be universally applied to the entire catalogue, allowing classification of many, if not most, of these features.

TABLE 3. QUARTILES FOR CORONA CHARACTERISTICS

	Eccentricity		
	q1	q2	q3
Domal (Y)	.505	.700	.735
Circular (G)	.410	.490	.610
Calderic (B)	.410	.510	.640
	Length (km)		
	q1	q2	q3
Domal (Y)	142	188	281
Circular (G)	129	167	225
Calderic (B)	75	102	150
	Dip (degrees)		
	q1	q2	q3
Domal (Y)	.051	.062	.082
Circular (G)	.057	.101	.169
Calderic (B)	.086	.128	.219

Note: Eccentricity, length, and dip given for each corona type with median (q2) and top (q3) and bottom (q1) quartiles.

DISCUSSION

In our study we examined the cratering record, distribution, and morphology of coronae. We argued that these preclude an impact origin for these features. A tectonovolcanic origin better fits our observations. We then presented and evaluated a model that considers coronae as manifestations of diapir evolution and found it consistent with characteristics of coronae.

What Mechanism Formed Venus's Coronae?

Crater density inside and near coronae argues for their being young and therefore volcanically and tectonically active features. Impact crater density within coronae lies below the planetary average; yet even with this lower density, the proportion of obviously tectonized craters considerably exceeds the number expected based on the total coronal area. Also, coronal distribution is more consistent with a volcanotectonic than with an impact origin. Coronae are strongly concentrated in the young BAT region and are closely associated with rifts, themselves sites of recent, if not ongoing, activity. We also show that longitudinal corona distribution, a pulse centered in the BAT region, clearly differs from the more random arrangement of impact craters. Even if we were to assume that all coronae are impact features, the combined corona and crater distribution is still not random in longitude (Fig. 6). Taken together, these observations are more consistent with coronae being young, active features, rather than ancient impact sites.

Are Coronae Venusian Analogs of Earth's Plumes?

Although there are hundreds of features that have been identified as coronae, only fifty-four of these have more than 50% of their interiors raised above the exterior (here classified as domal and potentially active). These correspond to 0.9% of the surface of the planet. Are these plumes on Venus? Here we define a "plume" as a deep-seated, long-lived thermal perturbation with a volcanic and tectonic surface expression. On Earth, the combination of plume and plate tectonic activity leads to Hawaiian-style island chains. On Mars, where no large-scale lateral tectonic activity has been documented, plume activity remains localized, resulting in the largest known shield volcanoes, such as Olympus Mons. On Venus, if coronae are in fact caused by plumes, there could be more than fifty. In comparison, Earth's currently active plumes have been variously numbered from a mere handful to well over one hundred. No unanimity exists on a catalogue of hotspots for Earth. For example, two analyses that correlated hotspot locations with geoid highs to infer the dynamic link (Chase, 1979; Crough and Jurdy, 1980) employed twenty-four and forty-two hotspots, respectively. So, comparing corona analyses, if all fifty-four domal coronae were active plumes, this would correspond to Venus's having an excess of 30% to more than 100% when compared with its sister planet, Earth. This number, though high, may not be unreasonable for a planet lacking plate tectonics to transport heat from the interior. Nonetheless, the presence of over six hundred coronae, implying that there was the same number of plumes in the last 1000–350 m.y. of Venus, does seem inordinately high, and therefore argues against a distinct plume source for each of these. We agree with Stofan and Smrekar (2005) that the regiones, such as Atla, Beta, Themis, and Phoebe, would better correspond to planetary plumes, i.e., large-scale uplifts. The smaller number of regiones (about ten), as discussed earlier, agrees more with our understanding about the capability of a planet's core to generate plumes that support uplifts. Ideally, the size and strength of individual plumes should be considered in this comparison, but these characteristics exceed the scope of this article.

The areal pattern of the domal coronae presents another argument against their having deep sources: in Figure 2, for example, note the four closely spaced domal coronae (yellow) between two contour lines around Atla's peak. That there are active plumes beneath each of these locations does not seem reasonable. In the terrestrial studies cited, hotspots are generally restricted to positive "residual" geoid regions, once the dominating effect of subduction has been removed. However, on Venus, coronae are found to correlate with midgeoid levels (Jurdy and Stefanick, 1999). This effect is apparent in Figure 9C, as almost a topographic limit, which the domal coronae—the ones we infer as active—cannot exceed.

Shallow diapirs may offer a more reasonable explanation for coronae. Admittance studies of several coronae (Hoogenboom et al., 2004) showed coronae as active upwellings, a result that has been interpreted to indicate isostatic compensation (Stofan and Smrekar, 2005). Based on fluid dynamic models, Hansen (2003) argued that coronae could be attributed to compositional diapirs, as opposed to the large rises and regiones, like Atla and Beta, for which thermal plumes are often invoked. We find that the observations presented in this article are consistent with a model of coronae as diapirs, either thermal or compositional, evolving through a sequence of stages, starting with uplift, followed by volcanism and development of annuli, and ending with collapse. As we have shown, a classification of coronae based merely on their interior topography leads to stages with a systematic set of characteristics. Younger coronae are larger, more eccentric, and flatter, and generally occur at higher geoid and topography levels.

A fuller understanding of coronae, and therefore of their underlying causes, could be achieved by extending the approaches we have taken to the entire set of 669 features mapped as "coronae" by Price and Suppe (1995). The study we presented in this article was more limited in scope and applied to the subset of coronae that had been categorized by DeLaughter and Jurdy (1999) by inspection. Any classification by visual examination is open to interpretation; thus we propose using an objective algorithm to assign each feature to a class based on its topography—whether uplifted, flat, or collapsed. The characteristics of each feature, such as tilt, size, ellipticity, altitude, geoid, and particularly circularity, can then be determined quantitatively, as we demonstrated here. We suspect that the group of coronae showing collapsed interiors may harbor a few impact craters, such as C21, as described in our analysis here. A complete and systematic examination of all features on Venus classified as coronae should allow further evaluation of the diapir versus impact models for origin of these enigmatic circular features.

The relationships among coronae, regiones, and chasmata are complex, but in all likelihood hold the key to understanding the resurfacing processes for Venus, and in turn, the global heat dissipation mechanisms. In the absence of Earthlike plate tectonics, plumes, whether on the scale of regiones or of coronae, must play an important role in both phenomena.

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DISCUSSION

3 December 2006, Warren B. Hamilton

Thousands of old, mostly circular structures with impact-compatible morphology and rim diameters from 3 to 2500 km saturate large tracts of both uplands and lowlands of Venus. Most of these old structures are ignored in conventional work, including that by Jurdy and Stoddard (this volume), and the small fraction that are considered at all are deemed endogenic and young. The well-preserved structures typically are circular-rimmed shallow basins with gentle debris aprons, often with external gentle circular moats, and often with internal central peaks or peak rings. Basins are superimposed with the cookie-cutter bites required by impacts but incompatible with endogenic origins. Doublets and composite shapes attest to disruption of many bolides by gravity and dense atmosphere. Superpositions and analogy with the dated youngest large lunar impact basin indicate most of these structures to be older than 3.85 Ga if they record impacts: the venusian landscape is relict from late-stage planetary accretion. See Hamilton (2005, this volume) for evidence, illustrations, and discussions. Superimposed on the old structures are ~1000 small craters, rim diameters of all but a few <100 km, their scarceness reflecting atmospheric destruction of most small bolides, acknowledged by all as impact structures and very conservatively designated.

Jurdy and Stoddard (this volume) minimally address these matters in their presentation of numerical arguments for the conventional assumption that the old circular structures formed during the last billion years by endogenic processes. From the thousands of these structures, they consider only a small, arbitrary subset, particularly conspicuous in radar backscatter imagery of uplands, of "coronae." These mostly are circular rimmed depressions with rimcrest diameters between ~70 and 500 km. They include fewer than half of the large quasicircular structures and fragments thereof visible in uplands; perhaps one-twentieth of the large variably filled structures, seen primarily in radar altimetry, of the twice-as-extensive lowlands; and none of the several thousand additional small, old circular structures in both uplands and lowlands. Jurdy and Stoddard (this volume) select "coronae" by arbitrary criteria that limit them mostly to uplands and hence err in reasoning that uplands and circular structures must be products of plumes and diapirs. Further, they wrongly deny the existence of structures transitional between the ~1000 small young impact structures and their selected structures and of old, small structures (see my papers for illustrations of both).

Jurdy and Stoddard (this volume) depict coronae as elongate and aligned within rift zones, and therefore endogenic. The conflict between these conjectural elongate structures and the actual mostly circular ones is clarified by their Figure 4. Their "coronae" are elongate blobs drawn arbitrarily outside those circular structures most obvious in low-resolution reflectivity, or even drawn to enclose several such structures each. Their analysis of these blobs is irrelevant. They dismiss, without discussion, the circular and composite structures actually at issue as "calderic depressions," despite lack of dimensional and geometric similarity to any modern terrestrial magmatic features.

Jurdy and Stoddard (this volume) present stacked radial topographic profiles through five young impact craters accepted by all, and through six coronae. They acknowledge that four (I say five) of these six coronae have impact-compatible topography but argue that because five of the six profiles have lower circular symmetry than do those of the accepted impact structures, all but one are endogenic. (The one they accept as an impact is indistinguishable visually from hundreds of other "coronae.") The perceived distinction reflects flawed methodology and the greater age and modification of coronae. The Magellan Stereo Toolkit software, presumed source of the profiles, adds artifacts and digital noise, which cannot be interactively edited, where radar brightness contrast is low and features are large, the common case with old structures (C.G. Cochrane, 2005, and written communications, 2006). Jurdy and Stoddard (this volume) magnify these defects with vertical exaggerations up to 160:1. The extreme exaggerations of their Figures 3 and 8 negate conclusions derived from those also.

The Jurdy and Stoddard (this volume) statements regarding distribution of accepted "young" impact craters are based on an early tabulation that undercounted craters in bedrock terrains. Their confident statements regarding ages and origins of surfaces, landforms, and coronae are merely intertwined assumptions that are false if the structures at issue record impacts. Their deductions regarding geoid and uplands are false if uplands include impact-melt constructs, as I advocate. Their references to my work and predictions are miscitations.

22 December 2006, Claudio Vita-Finzi

To the outsider it must seem that we are going round in circles, or perhaps ovoids. For example, Jurdy and Stoddard (this volume) suggest that interpreting coronae as impact craters would result in a crater density for the BAT region of Venus indicative of a "somewhat older than average surface age," whereas they know it is relatively young because it lacks impact craters and boasts many rifts that are also poor in impact craters. Such arguments cut no ice with those who draw no distinction between coronae and craters. Even the statistical dialogue is not conducted on a single wavelength: measures of circularity are neither here nor there if you have decided that craters may be deformed by erosion or tectonics.

Perhaps we should move on to more productive matters. Three come immediately to mind. First, we need to know the varying atmospheric and geological conditions under which venusian impact craters formed, and this we can do only by dating them using criteria other than crater density. Second, the isotopic evidence points to a wetter past. When was it, how wet was it, and did impact history have anything to do with its demise? Third, if some, several, or all the coronae originated in plumes or diapirs, can we construct a model for the interior of Venus that can support them simultaneously or serially? But the first step is surely to follow Hamilton in looking at all quasicircular structures on Venus and not just those we call coronae, whereupon—witness the fine image by S.W. Tapper in Vita-Finzi et al. (2005), Figure 11, p. 821 (reproduced here as Fig. D-1)—we find a landscape as lunar as the Moon's.

27 December 2006, Richard J. Howarth

At the end of the initial paragraph of their section on testing the impact hypothesis, Jurdy and Stoddard's quotation from Fisher is outdated: the approximation to a normal distribution is quite inadequate for small samples. The authors do not even say what their "count" of four is supposed to be—it must be the

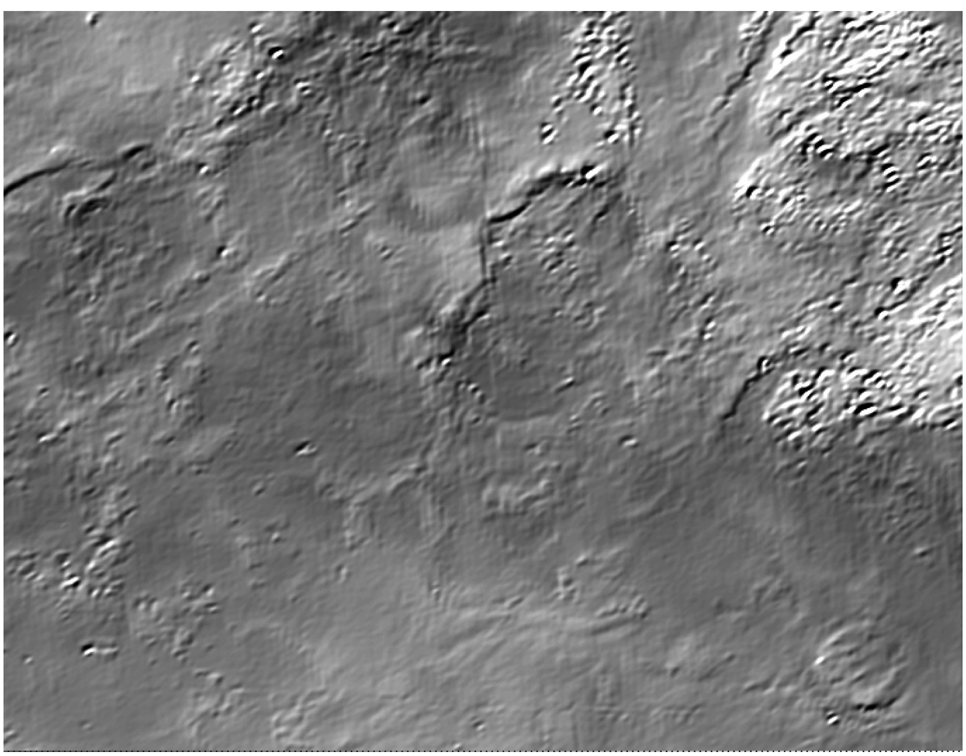

Figure D-1. Shaded relief image generated from Magellan altimetry of part of Scarpellini quadrangle illustrates subtle multicratered topography. The crater at bottom right has a diameter of ~200 km.

number of occurrences in so many sampled units. Even if these are implicit, and they ought to be explicit, e.g., in *n* cells of *X* by *X* km on the surface of Venus you only find four instances, etc. (see Howarth, 1998, for a survey of recent results on this topic).

Jurdy and Stoddard (this volume) talk about a "random" distribution without specifying what they mean by it. In fact, they are almost certainly talking about a Poisson distribution. In the second paragraph of their section on circular symmetry, they write of "profiles cross-correlated at only 25–30% of perfect cross-correlation." This kind of statement is inadequate. The sample size (i.e., number of data points), the type of metric used to assess the "cross-correlation," and the results of a statistical test of significance should all be given.

Even had these topics been adequately addressed, Jurdy and Stoddard's statistical assertions seem to me to add little weight to the key arguments, which are essentially geological and have been addressed, e.g., by Vita-Finzi et al. (2005).

9 January 2007, Ellen R. Stofan

Jurdy and Stoddard (this volume) describe coronae, a feature type that has been recognized in the peer-reviewed literature since their first identification in Venera radar images of the Venus surface (e.g., Barsukov et al., 1986; Basilevsky et al., 1986; Pronin and Stofan, 1990; Stofan et al., 1991; Head et al., 1992; Janes et al., 1992; Squyres et al., 1992; Namiki and Solomon, 1994; Stefanick and Jurdy, 1996; Hansen, 2003; Johnson and Richards, 2003; Hoogenboom et al., 2004). The majority of the community working with Venus data clearly differentiate between impact craters and coronae, as each has distinct morphologies and distributions. Jurdy and Stoddard (this volume) provide a clear and concise overview of the characteristics of coronae and why an impact origin is not consistent with these characteristics.

Their article provides clear evidence as to why their origin is related to endogenic processes. Endogenic processes are capable of producing depressions, and several models have been discussed in the peer-reviewed literature that are consistent with the observed range of corona topography (<1.0 km to >2.0 km) (e.g., Koch and Manga, 1996; Smrekar and Stofan, 1997). The impact cratering process, on the other hand, dominantly produces highly circular depressions. Clearly some coronae are depressions and some coronae are circular, but it is important to understand that both exogenic and endogenic processes can produce circular depressions and to focus on the evidence that allows one to determine which cause is more likely. As Jurdy and Stoddard (this volume) conclude, the data clearly support an endogenic origin.

18 January 2007, Warren B. Hamilton

Just the place for a Snark! I have said it twice:
That alone should encourage the crew.
Just the place for a Snark! I have said it thrice:
What I tell you three times is true.

Lewis Carroll

Vita-Finzi et al. (2005) and I (Hamilton, 2005, and this volume) argue that the thousands of circular venusian structures, mostly rimmed depressions that reach giant sizes and that predate obvious small, young impact structures, are products of ancient impacts. Although early interpreters of low-resolution venusian radar imagery recognized this possibility, Stofan (e.g., Stofan et al., 1985) and a few others speculated, years before detailed imagery became available, that Venus is too earthlike to preserve a primordial surface; hence, the circular structures must be young and endogenic. This conjecture soon became dogma, and the impact option has seldom been mentioned since. Broadly conflicting young-endogenic classifications and genetic rationales for some of the circular structures have been presented in hundreds of papers by Stofan and by many others (e.g., Jurdy and Stoddard, this volume), but the great majority of circular structures that are candidates for old impacts have been ignored by Stofan and most other venusian specialists. Many of these structures are huge and, if products of impacts, must, by analogy with dated lunar structures, be older than 3.8 Ga. The structures are mostly or entirely older than the small impact structures, as accepted by all observers, that conventionally have been assigned maximum ages of somewhere between 0.3 and 1.5 Ga on the basis of poorly constrained calculations of the effect on fragile bolides of the extremely dense venusian atmosphere; ages reach 3.8 Ga in my terms.

Few post-1988 mainline papers mention the impact option, and none has rigorously evaluated it, but Stofan here implies that because a number of papers, including five of her own and the chapter in this volume by Jurdy and Stoddard, agree that the circular structures are endogenic, and because the manuscripts were peer-reviewed (by other specialists who also assume endogenic origins), endogenic origins should be accepted. That the authority-by-repetition thus appealed to is poorly supported by evidence is shown by Stofan's many papers, and that the implied consensus does not exist is shown by the mutual incompatibility of her evolving speculations with those by others including Jurdy and Stoddard (this volume).

Stofan's papers deal with various venusian features that she regards as products of endogenic magmatism, mostly intrusive, despite their complete dissimilarity to any modern terrestrial structures. Her papers have concentrated on 400 or so "coronae," an arbitrary subset of conspicuous midsize circular structures. She has presented conceptual and numerical models wherein assumed parameters and unearthly processes enable endogenic results, but the models do not explain the characteristic circularity of the rimmed depressions except as local coincidences. Stofan's statement here that "endogenic processes can produce circular depressions" is but wishful thinking with regard to the thousands of examples with rim diameters up to 2000 km. Her papers have not addressed the common impact-compatible morphology, whereas even the anti-impact Jurdy and Stoddard chapter in this volume acknowledges that three of the six coronae whose morphology it considers in detail "appear crater-like" and that one of those three likely is an impact structure and the other two may be. The great majority of the old circular structures in the plains, which comprise two-thirds of Venus, are excluded from Stofan's studies, so her published statements about restricted distribution of coronae are invalid with regard to the broad population of structures at issue, and her global-dynamic speculations cantilevered from those statements also are invalid.

Stofan here notes, correctly, that "The impact cratering process . . . dominantly produces highly circular depressions" but then implies ("some coronae are circular and some coronae are depressions") that such structures are but a minor venusian type. The reader need look no further than the plains image in Figure D-1 to see that circular depressions are the rule. Stofan and Smrekar (2005) themselves stated that "the most typical shape for a corona is a depression or rimmed depression." The several papers by Stofan that mention the impact option dismiss it with arguments that I refuted in my papers as irrelevant because most of them (like most arguments in the Jurdy and Stoddard chapter in this volume) address only a biased subset of the circular structures, chosen by criteria that limit their geographic and size distributions, and further deal not with the circular rimmed depressions at issue but with imagined boundaries far outside them or even outside groups of the structures.

10 February 2007, Donna M. Jurdy and Paul R. Stoddard

In his discussion, Hamilton criticizes our data set and definition of the outlines of the features we analyze as arbitrary. Both statements are inaccurate. As we stated in our chapter, we used the data sets of Stofan et al. (1992), Magee Roberts and Head (1993), and Price and Suppe (1995), which in turn were not picked arbitrarily but based on a defined set of observed topographic, structural, and volcanic features. We used outlines that were mapped by Price and Suppe (1995) based on volcanic flows related to the structures, as interpreted from the radar imagery. We documented our use of the subset of the classified corona catalogue that could be matched with those 669 distinct features mapped by Price and Suppe (1995) as "coronae," which they defined in their catalogue as "circular to irregular volcanic-tectonic features characterized by an annulus of concentric deformation."

Hamilton suggests that if we were to pick the outlines of the features "correctly," we would find most to be circular to near-circular and cites our Figure 4 as evidence. Even if we were to accept this criticism, many of the internal structures in Figure 4 are still clearly noncircular. Dhorani and Ludjatako are clearly oblong, and Atete, Krumine (the northern part, as this is one that may have had "several such structures"), and Javine are all irregularly shaped. Others, such as Dilga, may be more circular, although Dilga was fairly round even as mapped by Price. Furthermore, our quantitative analysis assesses circularity not based on the mapping by Price but on Magellan topography. Finally, it must be pointed out, again, that circularity does not necessitate impact origin, but noncircularity requires a much more complex history, with many other implications, than a simple impact.

The remaining major concern Hamilton raises is the inappropriateness of the Magellan Stereo Toolkit software for features of the size we analyzed. We agree, which is why we did not use it for the study we report in this volume. (However, we did reference other studies that employed stereo imaging; this may be where the confusion arises.) Stereo imaging for high-resolution topography can be attempted for only about 10% of Venus's surface with multiple radar coverage. For our topographic analysis, we used the nearly global Magellan altimetry data.

In his discussion, Vita-Finzi suggests that we engage in circular reasoning. Although we admit that many of our arguments are based on the circularity of craters and lack thereof of many coronae, we disagree that our BAT region argument is circular. The BAT region has many indications of being more active, and therefore younger, than the average age of the venusian surface—uplifts with associated high geoid values, extensive rift systems, and the high concentration of tectonized, embayed craters as well as volcanic activity—all independent of raw crater counts. Crater Uvaysi retains its parabolic halo, indicative of the most recent 10% of craters. The severe modification of this parabola-associated crater dates tectonic activity as having occurred recently. Furthermore, independent stratigraphic study of the BAT region to neighboring areas also shows it to be young (Basilevsky et al., 1997).

Vita-Finzi correctly points out that tectonics can change the shape of craters, and erosion can modify, to some degree, the circularity as measured in our chapter. However, particularly for tectonized features, one would expect all features in a region to be elongated in more or less the same direction. Even with multiple tectonic events, the latest will be imprinted on all features. Analysis of corona orientation does not support this.

The correlation percentage referred to by Howarth is the standard cross correlation between the test and average profiles, divided by the autocorrelation of the average profile. The number of data points per profile was uniform for each feature, ranging from 41 for the smallest to 108 for the largest features.

Howarth has commented that our use of Fisher's description of sampling errors is outdated. However, Fisher's discussion of sampling errors in counting objects (Fisher, 1973, sect. 15, p. 57) is both clear and understandable as well as familiar to Earth scientists. It is, of course, based on assuming a Poisson distribution. We had noted the limitations of small sample size for some counts. We maintain that the statistical analysis of craters has utility in establishing the relative ages of planetary surfaces.

Stofan in her discussion gives a historical perspective on studies of Venus's coronae. We thank her for comments and appreciate her insightful summary of past work.

None of the criticisms has seriously addressed our distribution arguments: Why are coronae, on average, less heavily cratered if they are indeed older features? Why do coronae tend to be more densely distributed in and near rift zones? If coronae were classified as craters, the BAT region with its surplus of coronae would then appear older than the average surface of Venus. What independent evidence exists for this?

We have presented a technique designed to quantitatively analyze features for crater-like morphology. Certainly this technique could be refined to consider better such factors as diameter/depth ratios, but we feel that even this rudimentary approach is much better than the eyeball method—with its associated subjectivity—for determining features' origins. Finally, we reiterate that only a complete, quantitative analysis of all mapped features identified as coronae would most conclusively address their origin.

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