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Corona Associations and Their Implications for Venus

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Geologic mapping principles were applied to determine genetic relations between coronae and surrounding geomorphologic features within two study areas in order to better understand venusian coronae. The study areas contain coronae in a cluster versus a contrasting chain and are (1) directly west of Phoebe Regio (quadrangle V-40; centered at latitude 15°S, longitude 250°) and (2) west of Asteria and Beta Regiones (between latitude 23°N, longitude 239° and latitude 43°N, longitude 275°). Results of this research indicate two groups of coronae on Venus: (1) those that are older and nearly coeval with regional plains, and occur globally; and (2) those that are younger and occur between Beta, Atla, and Themis Regiones or along extensional rifts elsewhere, sometimes showing systematic age progressions. Mapping relations and Earth analogs suggest that older plains coronae may be related to a near-global resurfacing event perhaps initiated by a mantle superplume or plumes. Younger coronae of this study that show age progression may be related to (1) a tectonic junction of connecting rifts resulting from local mantle upwelling and spread of a quasi-stationary hotspot plume, and (2) localized spread of post-plains volcanism. We postulate that on Venus most of the young, post-resurfacing coronal plumes may be concentrated within an area defined by the bounds of Beta, Atla, and Themis Regiones. © 1998 Academic Press

INTRODUCTION

Some of the most intriguing geologic terrains seen in the new Magellan data contain numerous assemblages of coronae. These features are defined by a dominantly circular structure consisting of an annulus of concentric ridges or fractures, an interior that is either topographically positive or negative, a peripheral moat or trough, and, commonly, numerous volcanic and tectonic landforms in the interior (Barsukov *et al.*, 1986; Stofan and Head, 1990; Pronin and Stofan, 1990; Stofan *et al.*, 1992; Squyres *et al.*, 1992; Head *et al.*, 1992). Coronae occur in linear chains and clusters (Stofan *et al.*, 1992). The morphology of coronae and the proposed sequence of events in the evolution are consistent with corona formation by the ascent of a plume of hot mantle material to the base of the lithosphere (Schubert *et al.*, 1989, 1990; Stofan and Head, 1990; Squyres *et al.*, 1992; Stofan *et al.*, 1992; Janes *et al.*, 1992; Sandwell and Schubert, 1992; Watters and Janes, 1995). A mantle plume origin has also been proposed for the much larger regional rises such as Beta Regio (Kiefer and Hager, 1991). On Earth, volcano-tectonic centers apparently related to mantle convection have a wide range of styles and sizes; the range of length scales in mantle convection and volcanic activity is an area of active research (Rabinowicz *et al.*, 1990, 1993).

The Magellan radar data for Venus present the scientific community with as many new questions about coronae as they answer. For example, can a genetic connection be established between adjacent coronae and can these features be dated stratigraphically? Is there a pattern to the age of coronae? Do the venusian "hotspot" features migrate or are they stationary?

In order to better understand the genesis of venusian coronae and perhaps answer some of these questions, we applied geologic mapping principles to determine stratigraphic relations between coronae and surrounding geomorphologic features. Two study areas were selected that contain many asymmetric, circular, multiple, and overlapping coronae occurring within a contrasting cluster and a chain. Both areas lie within the major volcanic center concentration between Beta, Atla, and Themis Regiones (i.e., Crumpler *et al.*'s (1993) BAT anomaly). The first area is west of Phoebe Regio (quadrangle V-40; centered at latitude 15°S, longitude 250°); it contains a cluster of many coronae that appear to be randomly distributed (Fig. 1).

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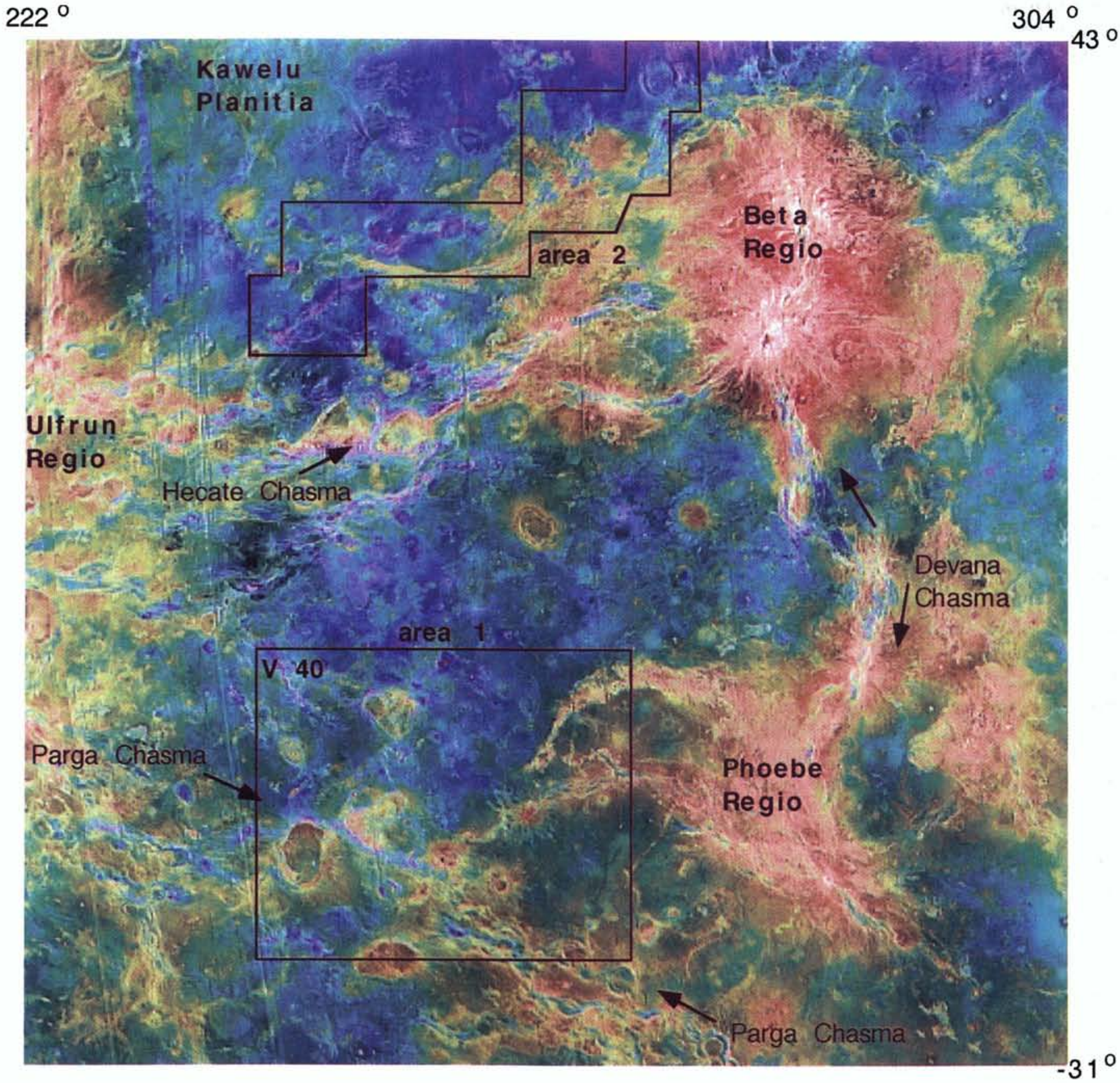


FIG. 1. Merged Magellan color altimetry and SAR data showing area of interest (USGS, 1997), location of 1:5,000,000-scale quadrangles of V-40 and area 2; north toward top; color key on Fig. 12.

In contrast, the second area, west of Asteria and Beta Regiones, contains a long chain of coronae that lead from approximately latitude 23°N, longitude 239° to about latitude 43°N, longitude 275° (Fig. 1). Earlier studies indicated no systematic variation in age along chains of coronae (Stofan *et al.*, 1992) and most coronal growth was fairly old relative to the global stratigraphy (Basilevsky and Head, 1995). However, results of this study suggest two groups of coronae: (1) those that are older and formed at about the same time, possibly in conjunction with a global resurfacing event; and (2) those that are younger than regional plains, some of which show systematic age progression along rifts or away from volcanic centers. Systematic age progression of coronae may be due to spread of large mantle plumes as they impinge on the lithosphere and perhaps minor migration of small mobile hotspots. Our work combined with that of other researchers implies that most of the young, post-resurfacing coronal plumes may be concentrated within an area defined by the bounds of Beta, Atla, and Themis Regiones.

METHODS

Relative ages for most units were established by stratigraphic relations; however, some deposits without decipherable stratigraphy could only be mapped as undivided material units. Owing to the side-looking mode of acquisition of the radar images, terrain sloping toward the imaging sensor appears brighter and spatially compressed compared to terrain that slopes away from the sensor (Ford and Plaut, 1993). Differences in surface roughness of units result in variation in brightness (Ford and Plaut, 1993); units with nearly identical surface morphologies are difficult to discriminate. Because of these characteristics of the Magellan radar images, many stratigraphic relations are based on very limited observable contacts and many tectonic features could only be mapped as lineaments.

In addition, the cumulative densities of impact craters are too low on Venus for determining ages at the 1 : 5,000,000 mapping scale. However, studies of impact craters on the entire planet of Venus from the Magellan images have led workers to hypothesize that some pervasive, near-global resurfacing event occurred a few hundred million years ago (Parmentier and Hess, 1992; Phillips *et al.*, 1992; Schaber *et al.*, 1992; Turcotte, 1993; Herrick, 1994). Additionally, Strom *et al.* (1992) noted that a global resurfacing event yields thermal evolution results consistent with numerical calculations of mantle convection in Venus (Arkani-Hamed and Taksöz, 1984). Therefore, the present surface, which still could be active, and the coronae are no older than that resurfacing event. The age of a venusian geologic unit can only be determined from superposition relations of its distal materials; because these deposits may not be representative of the entire age span of the unit, their placements on the correlation keys should be considered data points without quantitatively constrained error bars.

AREA 1: PARGA CHASMA (V-40 QUADRANGLE)

Trending northeast across the northeast quadrant of quadrangle V-40 is the tessera high that is the terminal end of the western arm of Phoebe Regio (Fig. 2). Trending northwest across the south half of the map area is Parga Chasma, a 1,870-km-long fractured depression that roughly connects Themis Regio (latitude 35°S, longitude 285°) and Maat Mons (latitude 0°S, longitude 195°). Southwest of the intersection of Parga Chasma with the western arm of Phoebe Regio, tessera material occurs as several isolated hills following the same northeast trend as the Phoebe Regio arm. East of its intersection with the tessera high, the chasma is offset 200 km to the south. Eighteen coronae are scattered throughout quadrangle V-40. A closer inspection of these coronae reveals nine closely spaced coronae (six that bound the linear fracture zone of Parga Chasma and a line of three coronae trending northeast of Parga Chasma, along another fracture zone); four distal coronae that bound Parga Chasma; and a distal uncinate (hook-shaped) chain of five small coronae unrelated to Parga Chasma (Fig. 2). For this paper, the nine closely spaced coronae will be referred to as area 1 and will be contrasted with coronae occurring in area 2, west of Beta Regio (Fig. 1).

Relations of coronae on quadrangle V-40 seem to suggest minor migration of small mantle plumes and spread of larger plumes at rift junctions. For example, previous mapping of V-40 revealed a systematic age and dimensional progression of the five small coronae (archaically termed arachnoids, i.e., coronae with radial fractures, to emphasize their fractures; Head *et al.*, 1992) occurring in the uncinate chain, indicating that the features likely formed from a small mantle plume in a manner similar to terrestrial hotspot features (Fig. 3; Chapman and Kirk, 1996). Other observations led to the interpretation that this mantle plume has migrated beneath a stationary surface (Fig. 3; Chapman and Kirk, 1996). Volcanism of these small corona features postdates emplacement of the surrounding plains.

Mapping of V-40 also revealed details about the area 1 coronae and the evolution of the Parga Chasma fracture zone (Chapman, 1996, 1998). In area 1, all of the coronae postdate the surrounding regional plains and six of the nine coronae found along Parga Chasma appear to have formed coeval with and are probably related to the development of the chasma. The usual, relatively symmetric pattern of concentric and radial structures of coronae is absent around those coronae associated with Parga Chasma. Instead, these structures have been bent around and deflected about the fractures, graben, and depressions of the chasma. Depressions of Parga Chasma even form sections of the outer moats or troughs of these coronae. These aspects and the interlayered stratigraphy of coronal flows adjacent to Parga indicate that these coronae are related to the growth of Parga Chasma. Other aspects indicate that area 1 coronae are related to a tectonic junction of rifts. With the exception of two coronae (mapped as units cd and cf, Fig. 4) at latitude 1.5°S, longitude 255° and at latitude 19°S, longitude 251°, all area 1 coronae are elevated, plateau-like features with mostly incomplete outer moats.

GEOLOGIC RELATIONS OF AREA 1

The oldest unit in area 1 consists of tessera material (unit t; Fig. 4). Tessera or complex ridge terrain (CRT,

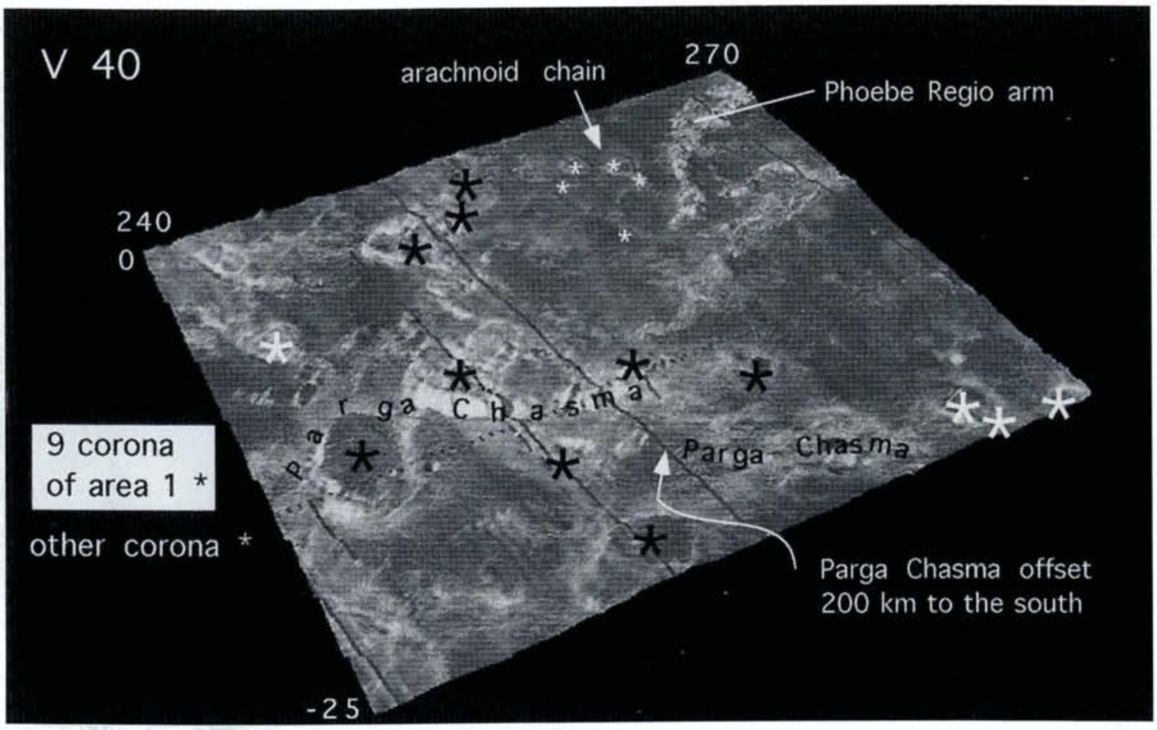


FIG. 2. Three-dimensional perspective view of quadrangle V-40 showing geomorphic features of interest (composed of left-looking synthetic aperture radar images; vertical exaggeration 10×; Kirk *et al.*, 1992).

Bindschadler and Head, 1991) was defined as a terrain type characterized by a completely deformed surface of ridges and troughs, intersecting at various angles, typically lying at higher elevations than surrounding materials, and likely resulting from extensive horizontal deformation (Basilevsky *et al.*, 1986; Bindschadler and Head, 1989, 1991). The tessera material comprises the highland terrain of the western arm of Phoebe Regio (Fig. 2) and an isolated hill along the trend of the arm within real 1 (Fig. 4).

Plains material (unit p) embays tessera material but is superposed by edifice unit 1 (unit e_1) at latitude 7.5°S, longitude 255° (Fig. 4). The outcrop of the edifice unit 1 is embayed by a flow of corona material unit a (unit ca) that can be traced to a 525-km-wide, unnamed, asymmetric corona at latitude 13°S, longitude 250°. Some flows from this corona have been deformed by and therefore appear to predate Parga Chasma. For example, south of the corona the chasma is 2.5 to 3 km deep, and the earlier unit ca flows from the corona extend to the opposite side of the chasma (Figs. 4 and 5). Other parts of the corona appear to be coeval with the chasma, as the southeast section of the corona's moat or trough is a part of the chasma (Fig. 5). Judging the age of features such as coronae and Parga Chasma based on deformation patterns alone is suspect because of the phenomenon of rejuvenated sympathetic structural trends; however, it is a valid method in the data-limited field of planetary geology and one that has been previously used to relate coronae and extensional belts elsewhere on Venus (Baer *et al.*, 1994).

At latitude 9°S, longitude 248.5° flows of corona unit a from the central asymmetric corona are overlain by flows from Javine Corona at latitude 5°S, longitude 251°, mapped as corona unit b (unit cb). Javine Corona is heart-shaped, a morphology that is controlled by regional tectonic activity prior to or during corona formation (Pronin and Stofan, 1990). Eastern flows of Javine Corona are overlain by flows and cut by graben of corona unit c (unit cc) at latitude 3°S, longitude 254.5°. Flows of edifice unit 2 (unit e_2) that were emitted from a caldera at latitude 3°S, longitude 257° are interbedded between unit cc flows and those of a corona to the north mapped as corona material unit d (unit cd; Fig. 6).

Deposits from unnamed corona unit a are overlain to the southeast by flows of corona unit e (unit ce) that were emitted from asymmetric Atete Corona (latitude 16°S, longitude 244°; Fig. 4), whose north boundary forms a 1- to 3-km-high cliff above Parga Chasma (Fig. 5). This portion of Parga is an arcuate segment that curves sharply to define the corona's boundary (Schubert *et al.*, 1994, Fig. 1). Because the moat or trough of Atete contains a section of Parga Chasma, the growth of Atete was likely coeval with development of Parga Chasma.

Flows of corona material unit f (unit cf) superpose corona unit e at latitude 20°S, longitude 248.5°. Some graben

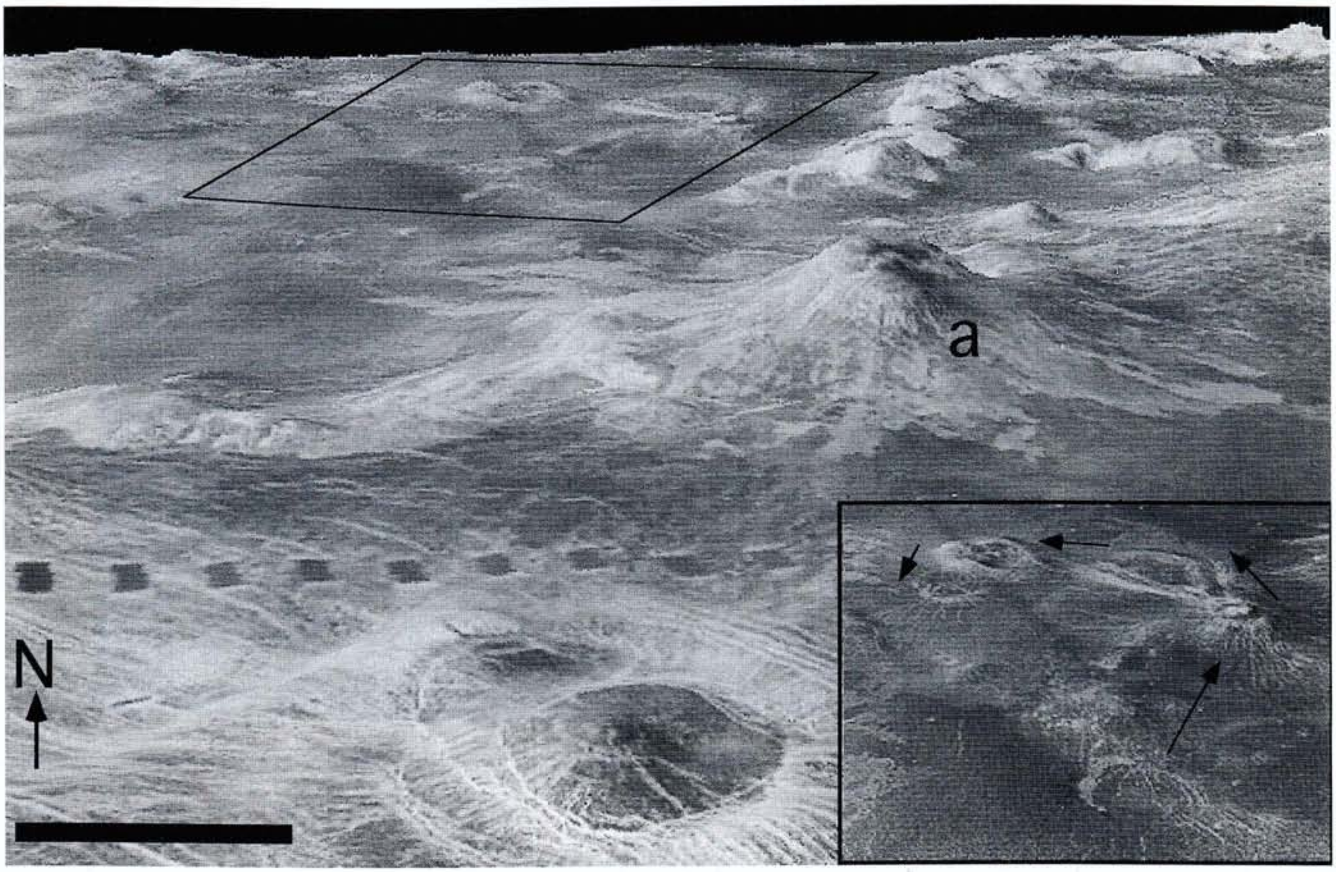


FIG. 3. Three-dimensional perspective view of northeast corner of V-40 (composed of left-looking synthetic aperture radar images; vertical exaggeration 10×; Kirk *et al.*, 1992); 100-km scale bar accurate for front of view; 2-km-high volcano marked "a" shown in **FIG. 10**; Nagavonyi Corona in foreground. Outlined coronae chain shown in rectangular view in lower right corner. Arrows in rectangular view show migration of coronae centers with time and may represent direction of possible movement of small migratory plume relative to a stabile surface.

and fractures that emerge from Parga Chasma extend south away from the Parga depression to the unit f corona, where the structures form part of the corona's annulus (Fig. 7). Therefore, emplacement of corona unit f was likely coeval with the development of Parga Chasma. Flows of corona unit f are overlain by outcrops of coronae material g and h (units cg and ch). Both outcrops of corona units g (Fig. 8) and h (Fig. 9) have associated annulus rings deflected and deformed to be symmetrical with structures of Parga Chasma, indicating the coronae units g and h were also likely coeval with the formation of Parga. Materials of corona unit h are in turn superposed by outcrops of corona material i (unit ci; Fig. 4). The material of corona unit i was emitted from Nagavonyi, a multiple corona at latitude 18.5°S, longitude 259.5° (Fig. 3). The east sections of Nagavonyi's annular rings are deflected from their circular paths to form straighter trends that match the trends of graben extending out of Parga Chasma. Where these Parga Chasma graben cut the flank of Nagavonyi, they emit flows mapped as queried corona unit i material. The unit designation of the flows is based on the interpretation that the deposits are flank fissure flows from Nagavonyi. The distortion of Nagavonyi's rings and the possible flank flows suggest that unit i was also deposited in conjunction with the development of Parga Chasma. Squyres *et al.* (1992) suggest that volcanism occurs early in the growth of a corona, followed soon after by early updoming and radial fracture. Mapping of area 1 supports this relation as all the coronal volcanic flows are cut by coronae fractures or Parga structures, with the exception of these late stage Nagavonyi flows.

Altimetry data show that the deepest sections of the northwest-trending depression of Parga Chasma lies within area 1 (up to 3 km deep, Figs. 4 and 5). Part of the deep section follows an arcuate path about the north end of Atete Corona (latitude 16°S, longitude 244°, Fig. 1), forming a sector of the corona's moat or outer trench. Another less dominant fracture zone, associated with three of the area 1 coronae, extends from the convex edge of this path, around the west side of the unnamed corona (at about

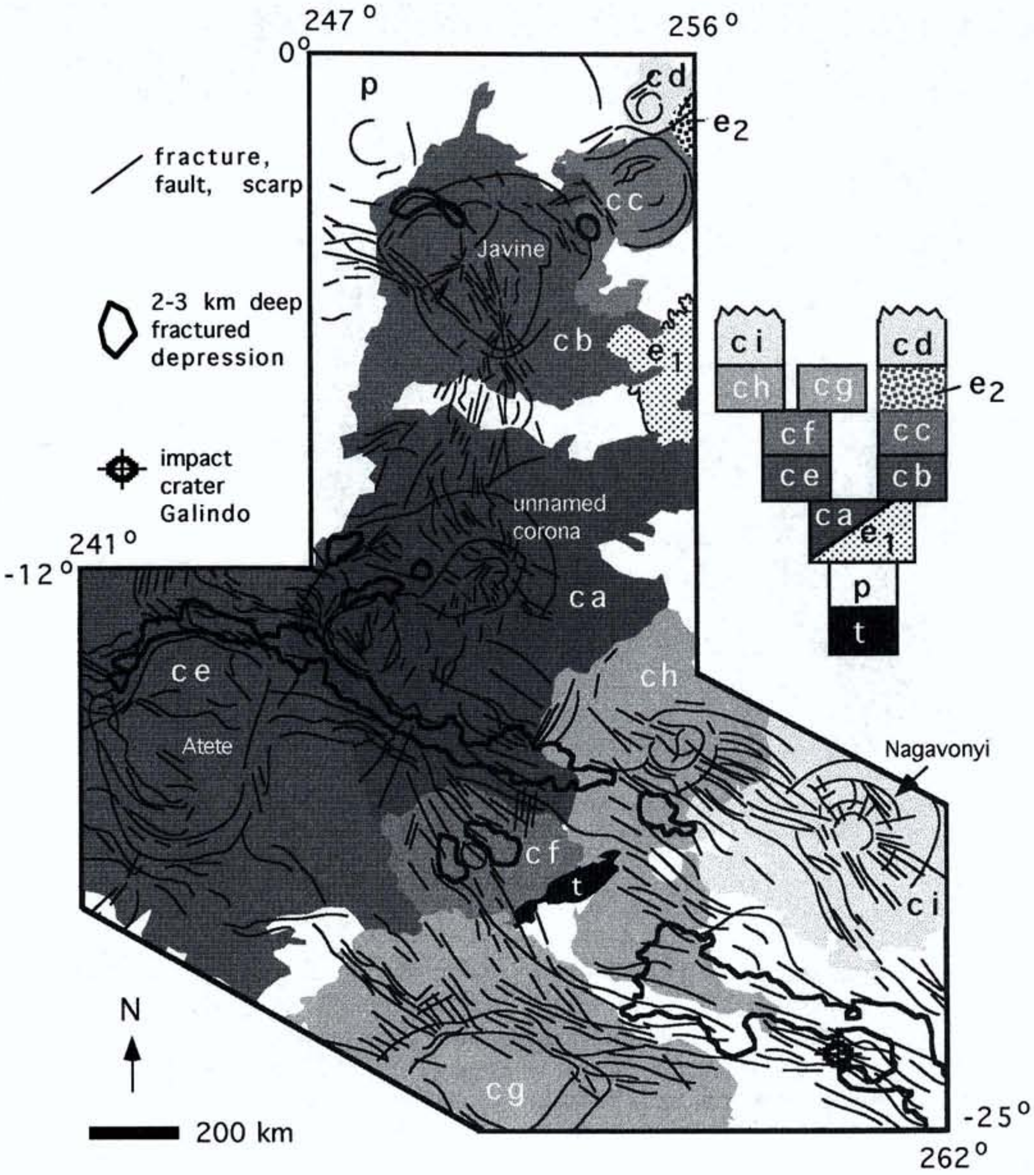


FIG. 4. Geologic map of nine coronae shown in Fig. 2 (part of geologic map of V-40; Chapman, 1998); t—tessera material, p—plains material, unit e_1—older edifice material, units ca through ci—corona material units, and unit e_2—younger edifice material; northwest trending 2- to 3-km-deep depression marks location of Parga Chasma.

latitude 12.5°S, longitude 250°), and continues to the northeast; this fracture forms a triple junction with Parga (Fig. 10). This northeast triple junction forms a 2-km-deep depression and part of the west moat of the unnamed asymmetric corona (Fig. 5); Parga forms the unnamed corona's south moat. This corona is centered at the triple junction and has produced the oldest stratigraphic volcanic flows (unit ca); the flows from the other coronae are systematically younger as the distance from each source coronae to the center of the junction increases (Fig. 4).

A 38-mgal positive gravity anomaly and a small positive geoid height are associated with Atete Corona; these data have led Schubert *et al.* (1994) to postulate formation by either thermally induced thickness variations in a moderately thick (about 100 km) lithosphere or a deep positive mass anomaly due to subduction or underthrusting. These authors prefer the interpretation that the gravity anomaly is due to a buried mass anomaly resulting from subduction because (1) the anomaly is associated with the concave side of the arcuate segment of Parga and (2) similar high gravity anomalies over other portions of the same chasma are absent.

However, map relations do not appear to support subduction at Parga (Chapman, 1996, 1998). The prolific num-

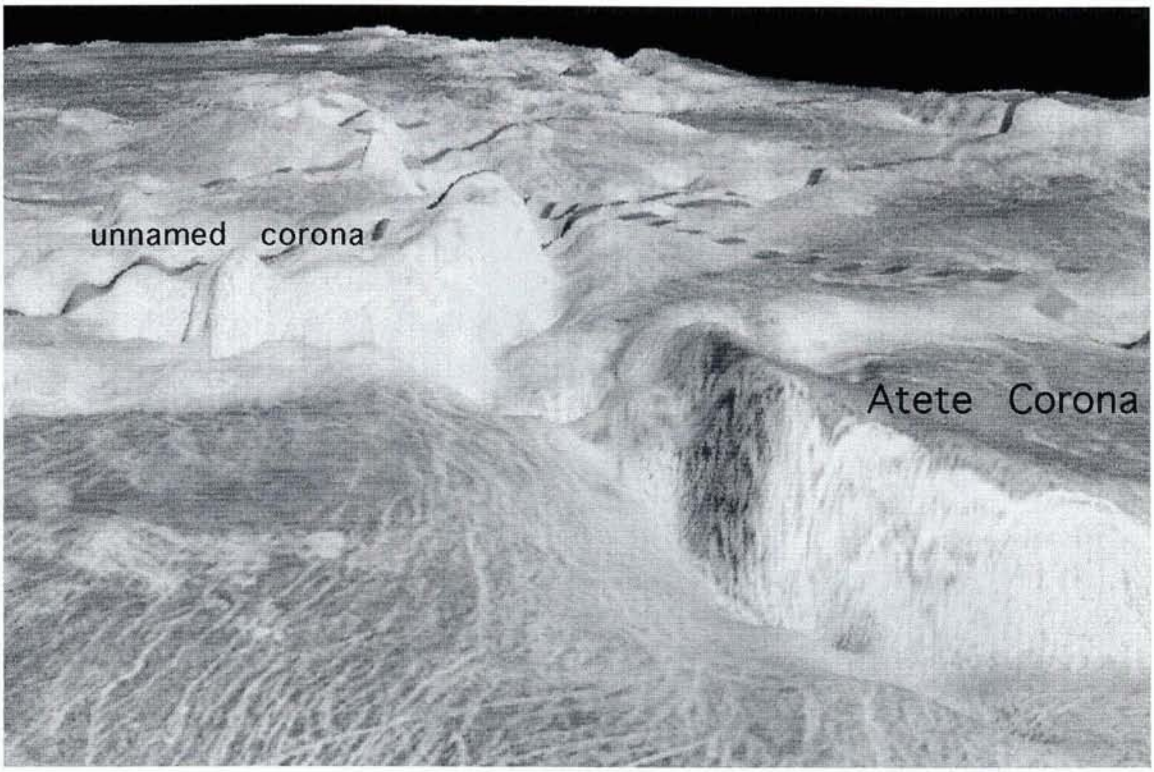


FIG. 5. Three-dimensional perspective view of northeast corner of Atete and an unnamed corona (composed of left-looking synthetic aperture radar images; vertical exaggeration 10×; Kirk *et al.*, 1992); Parga Chasma forms the depression between them; view toward the southeast looking along Parga Chasma.

ber of graben in the map area and possibly the broken, extended nature of the Phoebe Regio belt argue for extension. Coronae clustering along the entire length of Parga Chasma have caused others to suggest that the chasma is a zone of rifting and extension (Stofan *et al.*, 1992). In addition, there is no evidence of a compressed highland or arc along and coeval with Parga Chasma. Rather, elevated coronae bound either side of the chasma and occur along the fracture zone to the north (Fig. 1). Furthermore, the arcuate bend of Parga seems to form part of a triple junction rift zone. On Earth, in three-branched rifts, generally two of the branches concentrate the tensional stresses, and the less active one functions as a buttress (Carracedo, 1994). Coronae, along both Parga and the less dominant northeast fracture zone, may represent rift-type clusters of aligned volcanic edifices. In terrestrial rift zones, most of the basaltic section is likely to be erupted from an elevated region above a rift and flow laterally away from the rift onto an adjacent continent (White and McKenzie, 1989). The placement of coronae on either side of Parga Chasma and their extensive flows away from the chasma are in agreement with this terrestrial eruption mode.

The three branches of the Parga triple junction suggest a "least effort" fracture as a result of magma-induced vertical upward loading (Luongo *et al.*, 1991), possibly related to local mantle upwelling of a quasi-stationary hotspot plume that could result in thermally induced crustal thickening (Fig. 10). Movement of the surface above the plume would tend to be uplift above and extension away from the triple junction as the plume rises and spreads beneath the surface (Olson and Nam, 1986; Koch, 1994). This rise and spread of a solitary large plume is in accordance with the systematic age reduction of the coronae away from the center of the triple junction. The relation can be modeled with plume spread propagating the rifts, coronae growth, and volcanism similar to the movement of 3 zippers away from the triple junction. In addition, the direction of coronae asymmetries trends along the rifts. Curiously, Ki Corona (450 km in diameter) exhibits structures that support lateral spreading of another diapir along southeast Parga Chasma (Willis and Hansen, 1996).

AREA 2: KAWELU PLANITIA AND BETA REGIO

Area 2 consists of a 6,000-km-long chain of 12 circular coronae between Kawelu Planitia and Beta Regio, beginning at latitude 22.5°N, longitude 239° (Fig. 1). The coronae in the chain are mostly in low-lying plains, but a fracture

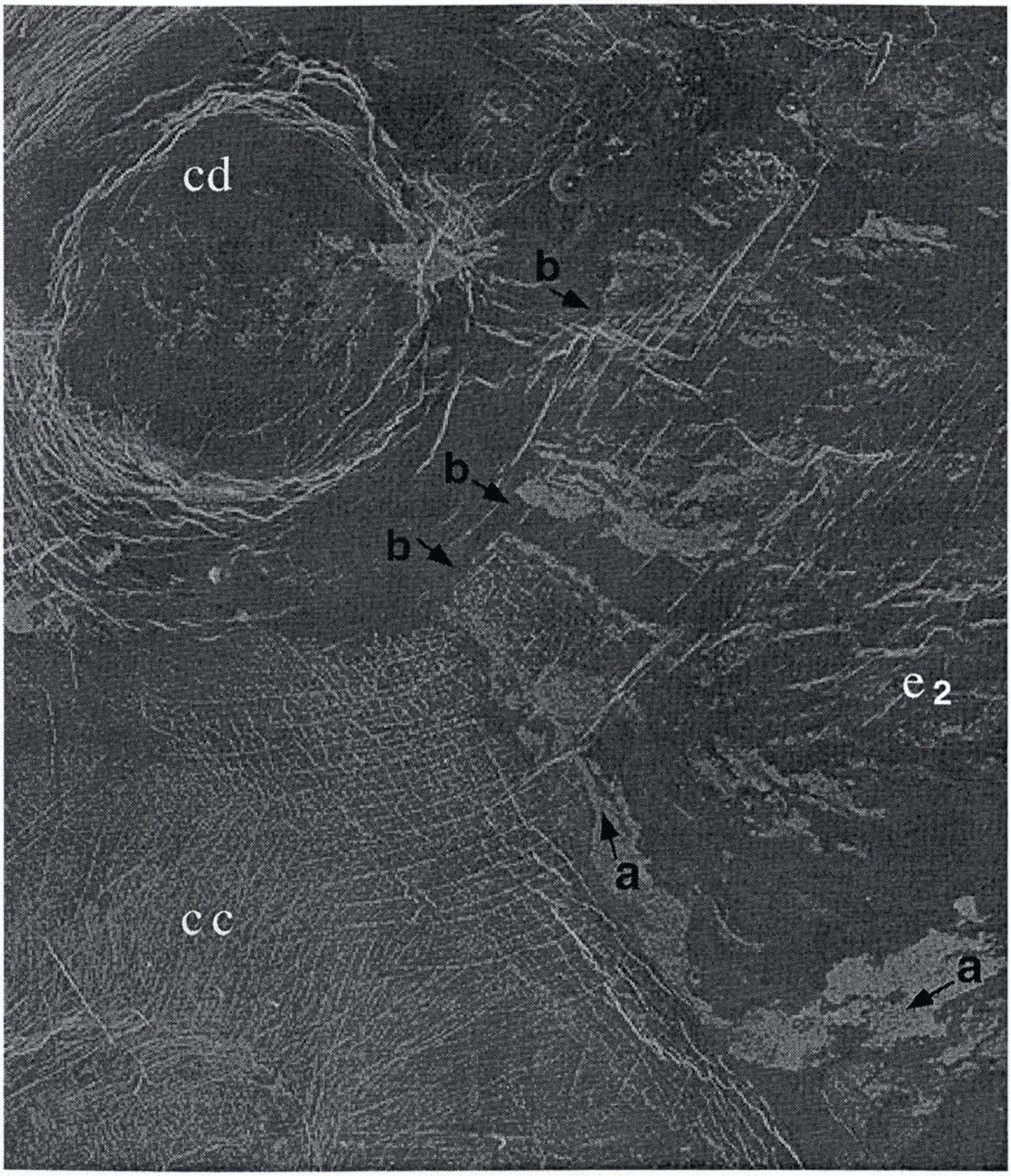


FIG. 6. Left-looking, synthetic-aperture radar (SAR) image centered at latitude 2°S, longitude 255° showing stratigraphic relations of units; annulus ring of corona (unit cd) in upper left corner about 70 km wide; north toward top. Volcanic flows (marked a) of edifice unit 2 (e_2) flowed toward and changed direction after they encountered preexisting topography of older material of corona unit c (cc). These flows are in turn overlain by material from corona unit d (cd) at arrows marked b.

zone that connects them intersects a mixture of plains and tesserae (Figs. 1 and 11). In contrast to the high relief coronae of area 1, the coronae of area 2 are only slightly topographically elevated in relation to their surrounding plain (Figs. 1 and 12).From the west, two arms of a bifurcating corona chain trend northeast and coalesce after crossing a western arm of Beta Regio tessera that extends through Asteria Regio; the chain shifts direction east to Asteria Regio, then shifts northeast, impinging on the north edge of Beta Regio, and ends at latitude 43°N, longitude 275°.

The minor fracture zone which connects the 12 coronae of area 2 is not associated with a trough or elevated terrain

FIG. 7. Left-looking, synthetic-aperture radar (SAR) image centered at latitude 19°S, longitude 251° showing graben and fractures (arrows) extending from Parga Chasma to the annulus of a corona (unit cf in Fig. 4); north toward top.

(Fig. 1). Mapping of area 2 revealed no systematic age or dimensional progression of 7 of the coronae occurring in the 12-member-long chain and a minor north to south age progression of the 5 westernmost coronae (Fig. 11). The coronae of area 2 have fully to partly raised circular rims. With the exception of a corona at latitude 23°N, longitude 240° (unit ce), all of the coronae have depressed interiors (Fig. 12).

GEOLOGIC RELATIONS OF AREA 2

As was true of area 1, the oldest unit in area 2 is also tessera material (unit t; Fig. 11). The tesserae occur in a western arm of Beta Regio and some nearby hills.

Older plains material (unit p_1) embays tessera material and is superposed by younger plains (unit p_2) at about latitude 42°N, longitude 270° and by varied corona materials at the west end of the area. Seven coronae occur within the older plains material as tectonic features. One of the seven, Rauni Corona, in the northeast corner of the area, is partly flooded by younger plains (unit p_2). The coronae of the older plains are only associated with very minor volcanic material or none at all and therefore flow superposition could not be used to date them stratigraphically. Their annulus ring fractures appear to be coeval, with the possible exception of a corona at latitude 32°N, longitude 258° (Zamin Corona), whose annular rings appear to terminate those of a corona directly west of it (Fig. 11). These

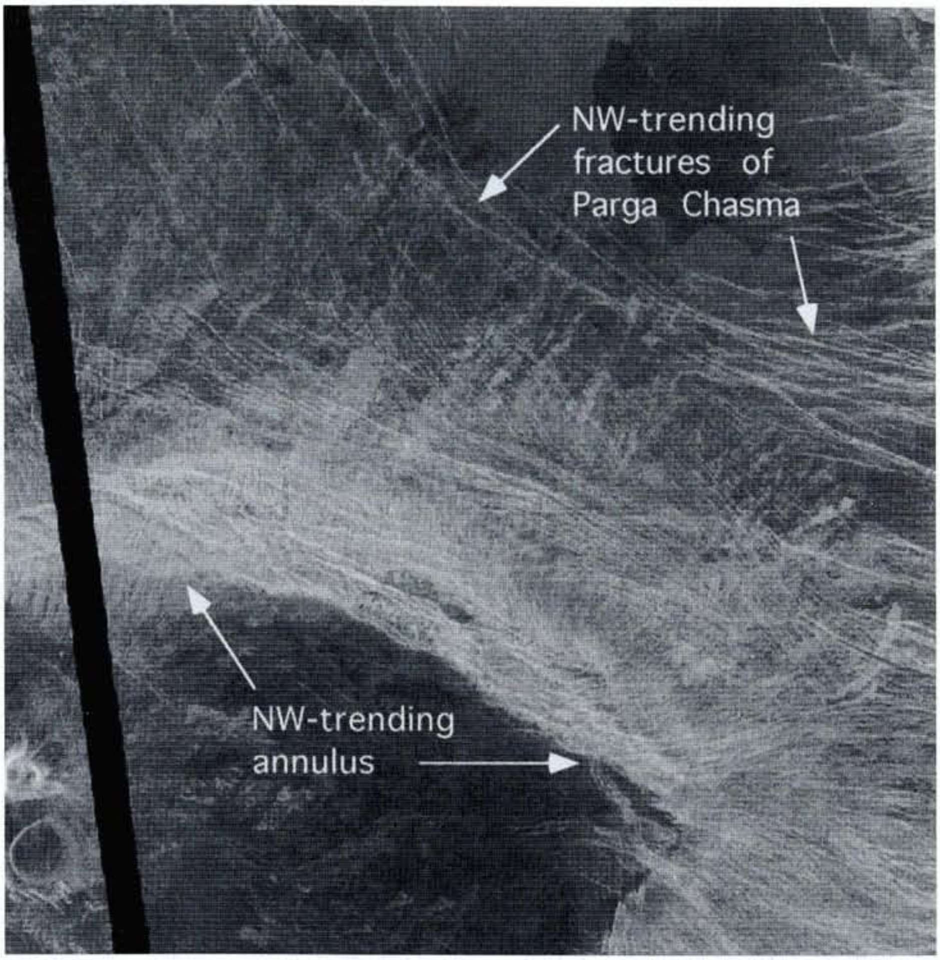


FIG. 8. Left-looking, synthetic-aperture radar (SAR) image centered at latitude 23°S, longitude 251° showing northwest trend of corona's annulus (unit cg on Fig. 4) mimicking trend of Parga Chasma fractures. Radial fractures from corona extend east into Parga Chasma; north toward top.

seven coronae show no systematic age progression along the chain nor do they appear to have obvious random age relations, but instead they seem to have formed synchronously (or perhaps randomly in a short period of time).

Flow materials of Mawu Corona (unit ca; feature lies just west of area 2) overlie older plains on the northwest corner of the map area but are cut by the fracture zone. These flows are superposed by corona material b (unit cb) emitted from an edifice to the southeast of Mawu at latitude 29°N, longitude 243°. Corona material b is embayed to the south by corona material c emitted from a small corona that is the northern, younger part of a multiple corona at latitude 24°N, longitude 244°. Directly southwest of the corona source of material cb is a corona that emitted a large amount of lava. Mapped as corona material d (unit cd), the flows partly flooded the annular rings of the older cb corona and flowed south over older plains material; the material postdates the fracture zone (Figure 13).

The youngest unit in area 2 is corona material e (unit ce) emitted from a feature at about latitude 23°N, longitude 240°.

The seven synchronous coronae of area 2 appear to have formed as structural features coeval with their fracture zone. They are associated with only minor volcanic flows and show no age progression; in fact, they appear to have formed at about the same time. They are constructed of tessera-embaying plains that have been deformed by the coronae and the fracture zone. Relations between the fracture zone and surrounding units indicate the zone and the coronae are fairly old and might have formed during or shortly after emplacement of the plains. This age assignment is compatible with the interpretation by Stofan *et al.* (1992) that the oldest coronae are in low-lying plains. Rauni Corona was previously described as an old feature based on topography and superposition (Pronin and Stofan, 1990).

Like the coronae of Hecate Chasma that show no systematic age relations (Hamilton and Stofan, 1996), a single

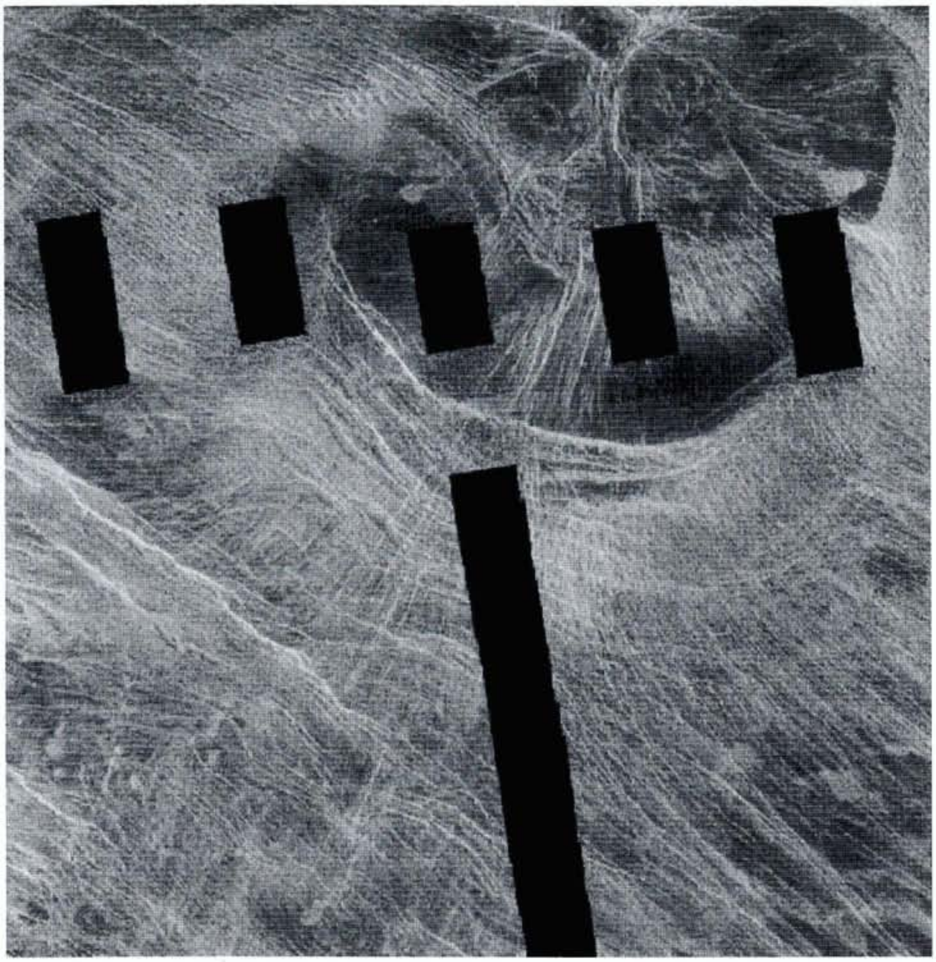
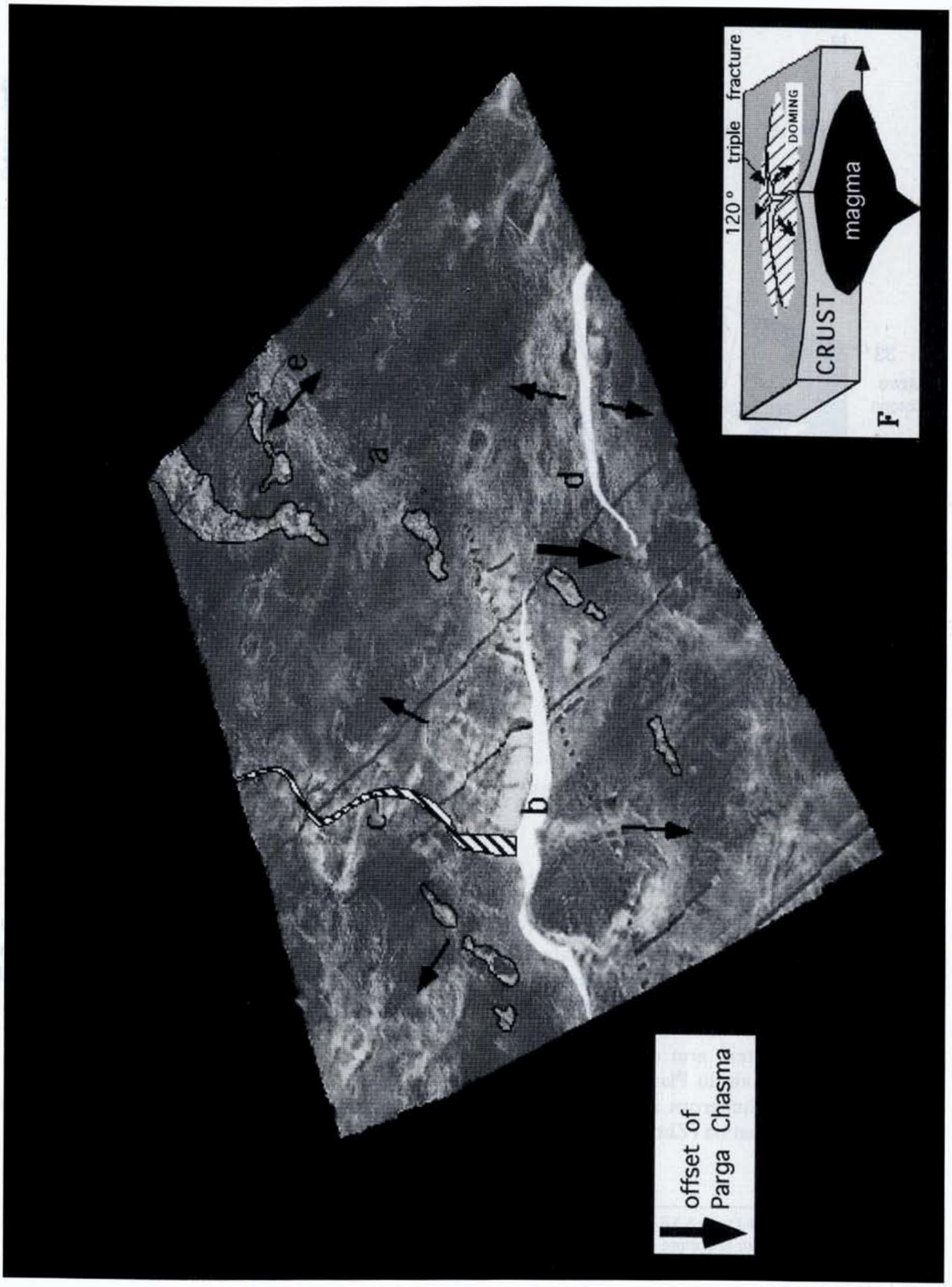


FIG. 9. Left-looking, synthetic-aperture radar (SAR) image centered at latitude 17°S, longitude 255° showing northwest trending fractures of Parga Chasma wrapping around corona's annulus (unit ch on Fig. 4); north toward top.

stationary thermal anomaly underlying a moving lithosphere is an unlikely origin for these coronae. The coronae may have been formed by upwelling similar to those observed at terrestrial mid-ocean ridges, but the lack of a trough and other evidence of much extension suggest little spreading along the upwelling zone. Instead, they are similar to the chains of seamounts and guyouts in the western Pacific. These seamounts are not associated with rifts, most date from the mid-Cretaceous, they occur randomly or in randomly oriented chains in a slightly older mid-Cretaceous oceanic plain, and they show no evidence of edifice age progression along the chains (Lincoln *et al.*, 1993; Larsen, 1995). One of the hypotheses of origin for the western Pacific is that all of the seamounts and the surrounding ocean floor resulted from a mid-Cretaceous superplume episode (Coffin and Eldholm, 1993; Larsen, 1995). Many workers are now considering previous superplume events and the possibility that the Earth has a "heartbeat" (Larson, 1995). (In fact, some believe that thermal effects on Earth act on 500 million year intervals

FIG. 10. Three-dimensional perspective view of quadrangle V-40 (composed of left-looking synthetic-aperture radar images; vertical exaggeration 10×; Kirk *et al.*, 1992) with illustrations; north is toward top; tessera outlined in black; arrows indicate inferred direction of surface movement; quadrangle is approximately 3,300 km wide. Flows from 2-km-wide volcano marked "a" embay arm of Phoebe Regio tessera. Deepest section of Parga Chasma indicated by white zone marked "b." Cross-hatched zone marked "c" is less deformed fracture zone trending northeast away from Parga. White zone marked "d" is an extension of Parga Chasma offset to south after encountering trend of tessera high. Relatively young extension zone marked "e" intersects volcano. Illustration F (in corner) shows surface movement away from triple zone fracture possibly similar to that formed by zones marked "b" and "c" on quadrangle.


offset of Parga Chasma
a
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d
e
120° triple fracture
DOMING
CRUST
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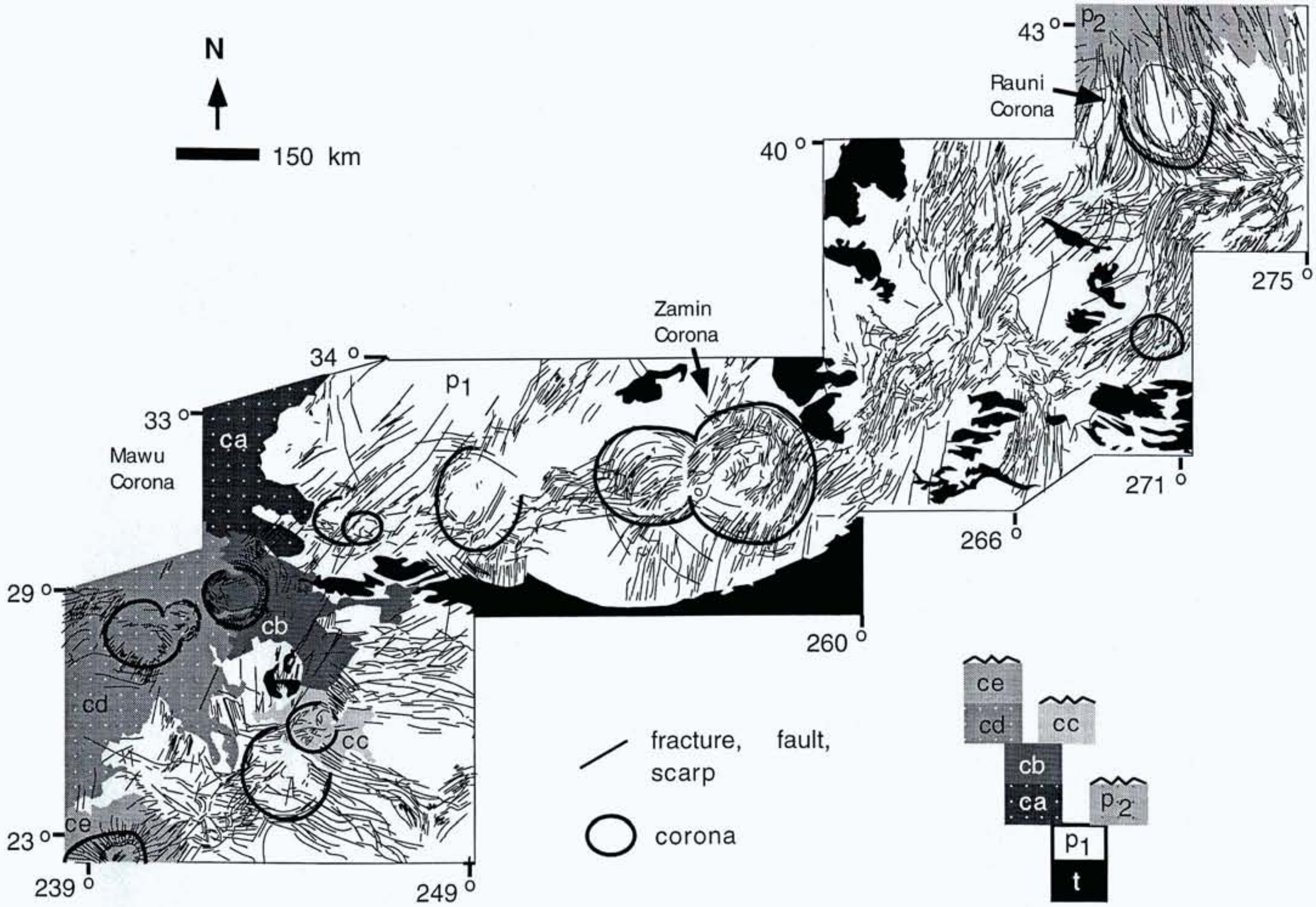


FIG. 11. Geologic map of area 2 (location on Fig. 1); t—tessera material, p_1—regional plains material, unit p_2—younger plains, and units ca through ce—corona material units.

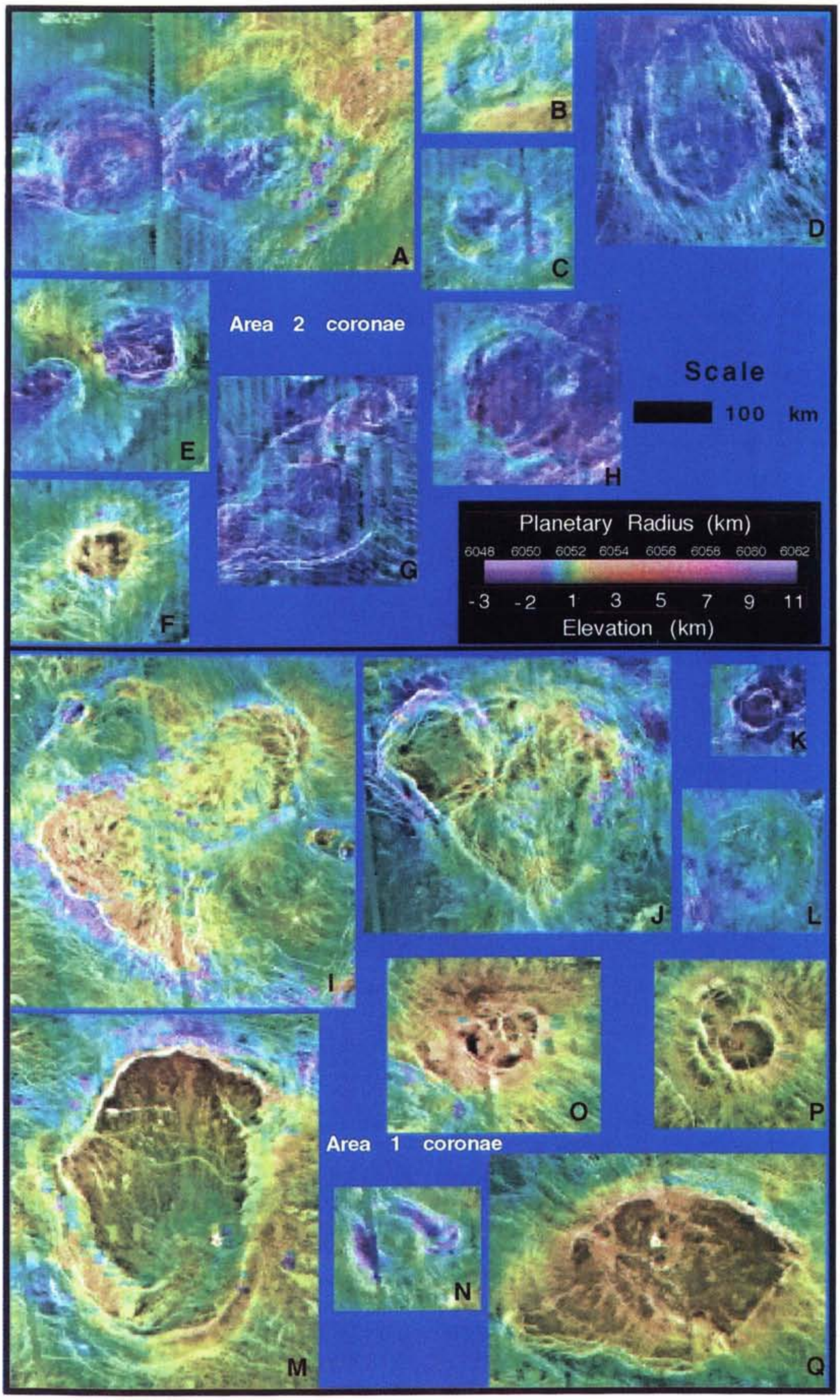
periodically causing the terrestrial continents to assemble into a single landmass; Murphy and Nance, 1992).

In contrast, the five western coronae of area 2 occur along a bifurcation of the chain and are associated with numerous volcanic flows that superpose older tesserae embaying plains; four are younger than the structures of the fracture zone. The age trend of these coronae is perpendicular to the end of the western arm of Beta Regio and lies on the south edge of Kawelu Planitia (a high plain) northeast of Ulfrun Regio. Numerous, large volume volcanic flows occur in Kawelu Planitia (Zimbelman, in review) and are perhaps related to localized upwellings. The age progression of the five coronae away from Kawelu Planitia may be related to an increase of volcanism away from the planitia in an event that continued after the formation of the fracture zone; the increase in volcanism could also be due to the spread of a large plume or perhaps multiple small plumes impinging on the lithosphere in a wider area.

DISCUSSION

Numerous models of hotspot dynamics exist and there are primarily two competing models for the generation of

FIG. 12. Color altimetry merged with SAR data (USGS 1997) showing coronae of area 2 and those of area 1; note that coronae of area 2 are generally topographically lower than and more symmetric, circular features in comparison to those of area 1. Area 2 coronae: A (Zamin Corona and unnamed corona to the east; latitude 32°N, longitude 258°), B (latitude 35°N, longitude 270°), C (latitude 30°N, longitude 246°), D (Rauni Coronae; latitude 41°N, longitude 270.5°), E (two coronae at latitude 29°N, longitude 242°), F (latitude 23°N, longitude 240°), G (latitude 23°N, longitude 244°), H (latitude 31°N, longitude 250°); and area 1 coronae: I (latitude 13°S, longitude 250°), J (Javine Corona; latitude 5°S, longitude 251°), K (latitude 1.5°S, longitude 255°), L (latitude 3°S, longitude 254.5°), M (Atete Corona; latitude 16°S, longitude 244°), N (latitude 19°S, longitude 251°), O (latitude 16°S, longitude 256°), P (Nagavonyi Corona; latitude 18.5°S, longitude 259.5°), Q (latitude 25°S, longitude 251°).


A
B
C
D
E
Area 2 coronae
H
Scale
100 km
F
G
Planetary Radius (km)
6048 6050 6052 6054 6056 6058 6060 6062
-3 -2 1 3 5 7 9 11
Elevation (km)
I
J
K
L
O
P
Area 1 coronae
M
N
Q

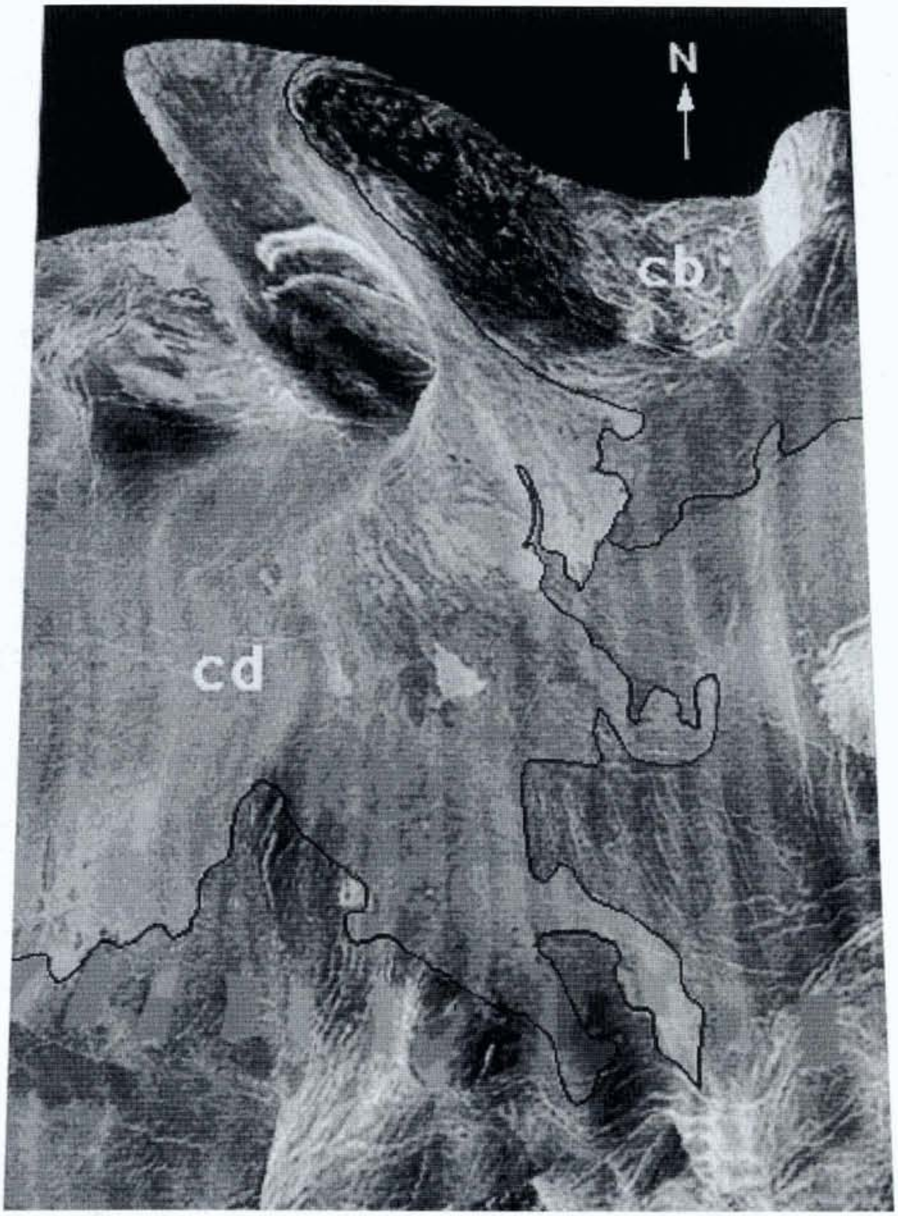


FIG. 13. Three-dimensional perspective view of part of area 2 centered at latitude 26°N, longitude 242° (composed of left-looking synthetic-aperture radar images; vertical exaggeration 10×; Kirk *et al.*, 1992) showing the voluminous flows (unit cd) of a corona superposed on older corona (mapped as unit cb) and fractures of regional plains.

coronae from mantle plumes. The phenomena responsible for the coronae may be directly analogous to the well-known terrestrial hotspots. However, it has been suggested that the process giving rise to terrestrial mantle plumes is inactive or very weak on Venus (Arkani-Hamed and Toksöz, 1984; Arkani-Hamed *et al.*, 1993; Tackley *et al.*, 1992). Tackley *et al.* (1992) recognized this difficulty, and they proposed that a novel, Rayleigh–Taylor-like instability might take place within the broad upwelling zones and might account for localized magmatism. In their model, plumes are driven by the buoyancy provided by partial melting (Tackley and Stevenson, 1993). The process is self-accelerating; the degree of melting, and hence the buoyancy, increases as the material ascends (Tackley and Stevenson, 1993). Scaling their numerical simulations to conditions on Venus, Tackley *et al.* (1992) estimated that the plumes would have a typical size of 250 km and that they would ascend on a timescale of 30 m.y. Magma-generation rates on the order of 1,000 km^3/Myr could be sustained over this period. This 30-Myr timescale is much shorter than the inferred few hundred million year average age of the surface (Parmentier and Hess, 1992; Phillips *et al.*, 1992; Schaber *et al.*, 1992; Strom *et al.*, 1992, 1994; Turcotte, 1993); therefore, many plumes could have formed and dissipated over the period preserved in the geologic record.

The two competing models of plume formation do lead to different predictions for the spatial and temporal distribution of coronae. Terrestrial experience suggests that plumes are localized, relatively stable, and long-lived (Wilson, 1963, 1965). Given that the terrestrial lithosphere moves relatively rapidly with respect to the mantle, the surface signature of a hotspot is a well-defined chain of volcanic features in which age increases systematically in one direction. If the lithosphere did not move with respect to the mantle, then the hotspot would build a single large volcanic construct or it might leave a track indicative of the motion of the plume through the mantle such as that observed by Chapman and Kirk (1996, Fig. 3). Alternatively, plumes triggered by melt-driven instability would occur throughout the zones of mantle upwelling (Schubert *et al.*, 1990; Schubert, 1992; Tackley *et al.*, 1992). Such plumes would tend to form much like bubbles in boiling water, leaving coronae with age relations that were virtually random.

However, rather than systematic or random age relations among coronae, what is observed in this study and another (Chapman and Kirk, 1996) is stratigraphically demonstrable systematic and synchronous relations between linearly trending coronae.

The seven synchronous coronae of area 2 (1) appear to have formed as structural features within older (tessera-embaying) plains material; (2) might have formed during or shortly after emplacement of the older plains; (3) are all circular features; (4) have interior depressions; and (5) have raised topography only along their annuli. Basilevsky and Head (1995) note that following tessera formation, extensive volcanic flooding resurfaced at least 85% of the planet. The seven synchronous coronae are likely old features as they occur within tessera embaying plains. Furthermore, they have morphologies consistent with an advanced state of development (Stofan *et al.*, 1992; Squyres *et al.*, 1992). Although it may be too premature to make global stratigraphic correlations, many other coronae elsewhere on Venus may also be old features. McGill (1994) noted that coronae in the region of Eisla Regio began to form very shortly after emplacement of the regional (tessera embaying) plains. In addition, from mapping of their random sample of 36 test areas on Venus, Basilevsky and Head (1995) suggest that most coronal growth was fairly old.

By analogy (see above), the synchronous coronae and the surrounding plains of area 2 are suggested to be the result of a superplume similar to the short-lived mid-Cretaceous superplume (Coffin and Eldholm, 1993; Larsen, 1995). However, if many coronae are old and date from regional plains, then their widespread global occurrence area is much larger in size than that of the terrestrial "superplume" in the western Pacific. It is more likely, based on the coronae's age and relation to regional plains, that they are related to the hypothetical, near-global resurfacing event that occurred a few hundred million years ago (Parmentier and Hess, 1992; Phillips *et al.*, 1992; Schaber *et al.*, 1992; Turcotte, 1993; Herrick, 1994). Global resurfacing could be expected to be responsible for the formation of a great many corona features planet-wide. Most likely, this may be the reason preliminary mapping of about 90% of the Venus surface by Stofan *et al.* (1992) detected no systematic variation in age along chains of coronae. Simply stated, most coronae may be old and date from the time of resurfacing. Based on morphology and superposition, Stofan *et al.* (1992) found that the majority of coronae are in the middle to late stages of evolution, with about a quarter of the population having very subdued morphology and topography indicating an old age.

If the hypothesis that most coronae are old is correct, how does that account for the observations of younger, systematically age-progressed coronae in both this and other studies (Chapman and Kirk, 1996)? What is the explanation for the ongoing, nonsystematic formation of coronae along and coeval with the evolution of Hecate Chasma (Hamilton and Stofan, 1996), or what seems to be ongoing formation of coronae along and coeval with the extension belts of northern Lada Terra (Baer *et al.*, 1994)? The answer to these questions could be that all of these younger coronae lie in a major volcanic center concentration between the Beta, Atla, and Themis Regiones (Crumpler *et al.*'s BAT anomaly, 1993) or are found elsewhere on venusian extension belts. Relative to the entire plant, a great many coronae are between Beta, Atla, and Themis regiones (Stofan *et al.*, 1992). In fact, Squyres *et al.* (1993) show that while the distribution of coronae over most of the planet is indistinguishable from random (density equals 0.73 coronae/10^6 km^2), the BAT region contains a significantly higher coronae concentration (>2 coronae/10^6 km^2). Although preliminary mapping by Stofan *et al.* (1992) found no systematic variation in age along corona chains, they did find a number of overlapping coronae that show a clear age progression, and 30 out of 35 of their multiple coronae are within the BAT anomaly. We agree that volcanism is concentrated in the BAT anomaly as noted by Crumpler *et al.* (1993), but we also suggest that much of this volcanism has occurred post-resurfacing and may still be active. This suggestion is supported by analysis of Magellan gravity data that confirm that Beta and Atla Regiones are active hotspots (Smrekar, 1994). Ironically, Basilevsky and Head (1995) based their suggestion that most coronal growth was fairly old on their random sample of 36 test areas on Venus, only one of which lies within the BAT anomaly.

Area 1 coronae (1) lie along a triple junction composed of a major fractured trough zone (Parga Chasma) and a less dominant fracture zone; (2) are high relief features; (3) contain numerous stratigraphically datable lava flow lobes; (4) are mostly asymmetric or multiple features; and (5) are younger than the surrounding tessera embaying plains. Briefly, area 1 contains an elevated rift with a tectonic rift junction and extensive coronal volcanism that postdates the regional plains. Keddie and Head (1995) suggest that there are two classes of volcanic rises on Venus: an areally large type with significant volcanism and rift zone formation and a smaller-scale type with extensive volcanism but moderate rifting. Stofan *et al.* (1994) point out that the volcanic rises of Atla and Beta Regiones lie at the major tectonic junctions of connecting rift zones (triple junctions). The tectonic rift junction of area 1 lies in the center of the BAT anomaly. Associated with Crumpler *et al.*'s (1993) anomaly are geologic characteristics interpreted as rifting and mantle upwelling. Could area 1's tectonic rift junction represent the incipient formation of an additional smaller region of the rift-type class within the BAT anomaly?

If the above suppositions are correct, what are the implications for the two competing models of plume formation? Older coronae plumes associated with resurfacing appear to be coeval, but could have formed randomly during a short period of time. Perhaps these plumes are indeed triggered by Rayleigh–Taylor-like melt-driven instability within the broad upwelling zones (Tackley *et al.*, 1992). Corona plumes that postdate resurfacing, discussed in this paper and others (Baer *et al.*, 1994; Hamilton and Stofan, 1996), appear to be mostly associated with rifting; the majority seem to occur either within the BAT anomaly or on active extension belts elsewhere. Younger coronae observed in this study may be the surface expression of spreading stationary mantle plumes. Minor motion of another younger small plume has also been observed (Chapman and Kirk, 1996). Therefore, post-resurfacing plumes are not occurring randomly like boiling bubbles in a pot, but are confined to certain areas on the planet and are long-lived to the point that local plume spread is evident, as is limited motion of small plumes.

CONCLUSION

Results of this study indicate that coronae either form in conjunction with older plains and show no systematic age progression or postdate older plains and occur in confined global locations, in some cases showing systematic age progression. The systematic age progression, rather than indicating motion of the surface relative to the mantle, indicates spread and movement of local mantle plumes. Mapping relations and Earth analogs cause us to suggest that older plains coronae may be related to a near-global resurfacing event perhaps initiated by a superplume or plumes. Other coronae of this study that are noticeably younger than the surrounding plains all lie within Crumpler *et al.*'s (1993) BAT anomaly, a concentration of major volcanic centers between the Beta, Atla, and Themis Regiones. We postulate that on Venus there currently exists a large-scale pattern of mantle circulation that concentrates most post-resurfacing coronal plumes within the BAT anomaly or along active extension zones elsewhere.

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