An alternative Venus

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ABSTRACT

Conventional interpretations assign Venus a volcanotectonic surface, younger than 1 Ga, pocked only by 1000 small impact craters. These craters, however, are superimposed on a landscape widely saturated by thousands of older, and variably modified, small to giant circular structures, which typically are rimmed depressions with the morphology expected for impact origins. Conventional analyses assign to a fraction of the most-distinct old structures origins by plumes, diapirs, and other endogenic processes, and ignore the rest. The old structures have no analogues, in consensus endogenic terms, on Earth or elsewhere in the solar system, and are here argued to be instead of impact origin. The 1000 undisputed young "pristine" craters (more than half of which in fact are substantially modified) share with many of the old structures impact-diagnostic circular rims that enclose basins and that are surrounded by radial aprons of debris-flow ejecta, but conventional analyses explain the impact-compatible morphology of the old structures as coincidental products of endogenic uplifts complicated by magmatism. A continuum of increasing degradation, burial, and superposition connects the younger and truly pristine of the young impact structures with the most-modified of the ancient structures. Younger craters of the ancient family are superimposed on older in impact-definitive cookie-cutter

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bites, not deflected as required by endogenic conjectures. Four of the best-preserved of the pre-“pristine” circular structures are huge, with rimcrests 800-2000 km in diameter, and if indeed of impact origin must, by analogy with lunar dating, have formed no later than ~3.85 Ga. Much of the venusian plains is seen in topography to be saturated by overlapping 100-600 km circular structures, almost all of which are omitted from conventional accounts. Several dozen larger ancient plains basins reach 2500 km in diameter, are themselves saturated by midsize impact structures, and may date back even to 4.4 Ga. Giant viscously-spread “tessera plateaus” of impact melt also reach 2500 km in diameter; the youngest are little modified and are comparable in age, as calibrated by superimposed “pristine” impact structures, to the least-modified of the giant impact basins, but the oldest are greatly modified and bombarded. The broad, low “volcanoes” of Venus formed within some of the larger of the ancient rimmed structures, resemble no modern volcanic complexes on Earth, and may be products of collapse and spread of impact-fluidized central uplifts. Venusian plains are saturated by impact structures formed as transient-ocean sediments were deposited. The variable burial of, and compaction into, old craters by plains fill is incompatible with the popular contrary inference of flood-basalt plains. Early “pristine” craters formed in water-saturated sediments, subsequent greenhouse desiccation of which produced regional cracking and wrinkling of the plains and superabundant mud volcanoes (“shields”). The minimal internal planetary mobility indicated by this analysis is compatible with geophysical evidence. The history of the surface of Venus resembles that of Mars, not Earth.

INTRODUCTION

Venus displays clear evidence for prolonged surface stability. It has unimodal topography, and no plate tectonics. Its rift systems record only minor extension (Connors and Suppe, 2001). Venus nevertheless is widely assumed to be about as active internally as Earth. This paradox is popularly resolved by assigning a young maximum age to the 1000 most-obvious impact craters, by rationalizing that the planet was wholly resurfaced endogenically before those craters began forming, and by assuming the thousands of older circular structures to have non-impact origins. I argue here that the morphology of those older structures instead requires them to be variably degraded and buried impact structures. The modified structures include many far larger than any young ones, and must be at least as old as 3.85 Ga if indeed they record impacts. The history of Venus has been profoundly misunderstood in conventional literature. Vita-Finzi et al. (2004, 2005) are among the very papers that have argued since about 1990 for the presence of old impact structures on Venus.

At least half of the 1000 accepted "pristine" craters in fact are modified, many severely, and there is a morphologic continuum from these, via increasing superposition, erosion, and burial, into and through the thousands of older structures. Many regions, both uplands and plains, are saturated by the old structures. There is much evidence for an ancient hydrosphere, and for thick plains sedimentation. This paper proceeds from a broad exploration of venusian problems (Hamilton, 2005). Some of the present conclusions (including those regarding preserved marine features and the non-magmatic nature of "volcanoes") differ markedly from those in my 2005 paper, but the two papers are complementary.

Imagery

The surface of Venus is known primarily from radar imagery obtained by the Venusorbiting spacecraft Magellan during 1990-1994. The most-used of this imagery is mosaicked synthetic-aperture-radar (SAR) backscatter (reflectivity), plotted as grayscale brightness draped on generalized topography. Recorded Magellan SAR resolution cells, before resampling to reoriented 75x75 m pixels, vary from 120x120 m to 120x280 m. The imagery differs profoundly from the photographic and optical-scanner imagery that it resembles superficially. Brightness of radar reflectivity is a function of slope (greatest from slopes facing the satellite), surface roughness at centimeter and decimeter scale near the radar wavelength (the rougher, the brighter), and the dielectric constant of surface material (the higher, the brighter). Substantial variations in topography often cannot be seen, important features can be invisible, and intersecting structures appear run together. Appearance of features varies greatly with their orientation and with the direction and inclination of the radar beam. Slopes facing the satellite are shortened and slopes away are lengthened, so symmetrical ridges appear to be hogbacks of dipping strata.

East-looking imagery with latitudinally-varying inclination provides the most extensive coverage. East-looking imagery with greater inclinations from the vertical is available for about one-sixth of the planet. Paired images can be viewed in optical or computerized stereoscopy; but the apparent lengths of slopes and vertical and horizontal positions of the ridges and valleys defined by their intersections vary with steepness and trends of those slopes, and confusing illusions abound in steep topography. Computerized stereoscopy relies primarily on matching brightness transitions, which can vary greatly, and migrate or disappear, with different look angles; mismatches are common, and false topography, with convincing visual aspect, can be generated (Cochrane, 2005). The MST (Magellan Stereo Toolkit) computer program, used widely (e.g., Matias and Jurdy, 2005) to generate perspective images and topographic profiles, is very unreliable where brightness contrasts are low and features are large, as commonly is the case with old structures, and can on the one hand mismatch wholly different features, and on the other add topographic noise to featureless areas (C.G. Cochrane, 2005, and written communications, 2006). West-looking imagery is available for part of the planet, but the incompatible brightnesses of the opposite look directions commonly preclude satisfactory stereoscopy. Venus global topography comes primarily from Magellan nadir measurements, which have low resolution and contain artifacts and noise. Most backscatter and altimetric imagery shown here was downloaded from the website http://astrogeology.usgs.gov/Projects/Map-a-Planet, which almost instantly provides a seamless mosaic of any area on its own sinusoidal projection.

Scores (hundreds?) of pseudoperspective diagrams (e.g., Grindrod and Hoogenboom, 2006; Grindrod et al., 2006; Krassilnikov and Head, 2003) of the circular structures have been published. The impact rim, basin, and apron morphology of most of the structures illustrated commonly are shown but are obfuscated by the invariably great vertical exaggerations (often unmentioned in captions or texts) of at least 10x, typically 20 or 30x, and sometimes even 50x, and by altimetric artifacts which also are exaggerated. (The one pseudoperspective plot in this paper has an exaggeration of only 3x.) Also common in the venusian literature are topographic profiles with even greater vertical exaggerations. Herrick et al. (2005, fig. 1-d) showed profiles across Chloris Mons (which is shown by Figure 8 of this report) with a vertical exaggeration of ~150:1, rendering the 1° slopes of the very low central dome within the crater as gigantic 70° slopes. Grindrod et al. (2006, fig. 3) similarly depicted a broad, low mound (Atai Mons), which rises within a circular rim 150 km in diameter, with a vertical exaggeration of 60:1. Many venusian interpretations (e.g., Jurdy and Stoddard, 2007) are based on illusions in such exaggerated and artifact-ridden illustrations.

Circular Structures

The surface of Venus displays thousands of circular structures that obviously are mostly older than the 1000 minimally-modified craters agreed by all observers to be of impact origin, and much of the surface is saturated by the old structures. Less than 1000 of the old structures are recognized in the conventional literature—most of the large ones, and nearly all of the small ones, are ignored—and are presumed endogenic. However, the better-preserved of these old circular structures share with the young impact structures the basin, rim, and apron morphology expected of impact origins, and have the requisite cookie-cutter superpositions. From these there are all gradations of greater modification, overprinting, and burial. Several thousand of the old structures have circular rims 200 to 2500 km in inner diameter, and if indeed of impact origin, even the youngest must, by analogy with lunar dating, be at least as old as 3.85 Ga.

Impact structures begin as transient excavated and imploded cavities, but floors of all but the smallest immediately rebound and, simultaneously, walls cave in. Final rims are far beyond initial large excavations, and are not perfect circles in anisotropic targets. Shock melting, decompression and delayed melting in very large excavations, and granular fluidization by shock without melting, may be extensive.

Conflicting Endogenic Conjectures. The endogenic explanations for the old circular structures have many imaginative variants constrained primarily by the assumption that plumes, diapirs, and other upwellings and downwellings must be responsible. Grindrod and Hoogenboom (2006), Herrick et al. (2005), Jurdy and Stoddard (2007), Krassilnikov and Head (2003), and Stofan and Smrekar (2005) provided recent additions to the conflicting speculations. Here is the list by Herrick et al. (2005, p. 1; I omit his citations to supporting publications) of some of the mutually incompatible conjectures for the origin of coronae, the most common label given large, old venusian structures dominated by circular rimmed depressions: "coronae are caused by plumes originating from a midmantle layer; coronae are caused by breakup of a mantle plume head; coronae form from plumes interacting with thin lithosphere . . . ; coronae are caused by detached diapirs, perhaps followed by retrograde subduction and or delamination; and coronae are formed by small, long-lived plumes from midmantle depths that evolve to delaminate the lithosphere." These hypothetical processes have no known terrestrial analogues. The Herrick et al. paper, like most others, does not mention impact origins as an option.

Nomenclature. Venusian literature is rich in unfamiliar terms that render papers opaque to nonspecialists. Some terms are shared with other planets, but the most-used are unique to Venus. The fewer than 1000 old circular structures that are acknowledged in the conventional literature, selected arbitrarily from the thousands that exist, are assigned labels that include arachnoid, astrum, corona, stealth corona, crustal plateau, mons, nova, patera, tessera, tick, and volcano, plus various hybrids. These terms are all used with exclusively endogenic connotations. The only common term, volcano, conveys a misleading impression of morphology, and may be incorrect in implying a magmatic construct.

Most abundant of the large circular structures are coronae (which mostly have raised rims enclosing basins), "volcano-tectonic features that are apparently unique to Venus" in the solar system (Grindrod et al., 2006, p. 265). The implausibility of such uniqueness vanishes if coronae, and the others, instead record a ubiquitous exogenic planetary process.

Numerical Modeling. Endogenic speculations often are accompanied by numerical modeling based on values and concepts assumed because they enable calculation of the desired results. Herrick et al. (2005, p. 11) conceded that their own modeling was based on "debatable and largely unconstrained" assumptions. Kaula (1995) recognized that such modeling, including his own, can amount to "wish fulfillment," and emphasized that all explanations of mantlecirculation causes of hypothetical resurfacing are contrived rationalizations. Anderson (2006) demonstrated that the common exclusion of pressure-varying parameters from such modeling renders it essentially useless.

None of the qualitative or quantitative endogenic conjectures account for the characteristic circularity and impact-like morphology and superpositions of the structures at issue.

Planetology and Plumology

The Moon's small to huge rimmed circular structures were widely regarded as products of endogenic processes until the 1960s. A few astute observers, from Grove Karl Gilbert to Robert Dietz, argued for impact origins and for preservation of a landscape dating back to the era of planetary accretion, but this view did not prevail until space-age evidence made it inescapable. Similarly, terrestrial circular structures now proved to record ancient impacts were commonly assumed, until even later, to be "volcanotectonic" or "cryptovolcanic."

Consensus regarding the large rimmed circles of Venus went in the opposite direction, from impact to volcanotectonic—and for the opposite reasons, conjecture trumping evidence. The mist-shrouded surface of Venus was seen first, in the 1970s and 80s, with low-resolution radar imagery, and many large rimmed circular structures were recognized. These have the size distribution and rim, basin (often with central peaks or peak-rings), and apron morphology expected of impact structures, and were early regarded as of possible impact origin, even though this required that they record very ancient accretion of the planet (e.g., Basilevsky et al., 1987; Grieve and Head, 1981; Masursky et al., 1980).

Theorists (e.g., Stofan et al., 1985), however, rationalized that preservation of ancient surfaces and structures on "Earth's twin" was impossible, and exported terrestrial plume conjecture to Venus to explain the planet's circular structures. Speculation regarding terrestrial plumes, hypothetical columns of hot material rising from deep in the mantle, became popular during the 1970s and 1980s. The present volume contains many papers expressing terrestrial pro- and anti-plume arguments; see also Foulger et al. (2005) and G.R. Foulger's website, www.mantleplumes.org, for many more papers on both sides of the debate. The physical and geochemical rationales presented for plumes are contradicted by all available information from the systems at issue, which instead indicate processes limited, or almost limited, to the upper mantle (Anderson, 2006). The geologic rationales for hotspot tracks and the like have been disproved. Nevertheless, venusian plume conjectures quickly became entrenched. Impact explanations were discarded, years before high-resolution imagery became available, in favor of a chain of suppositions linked with a few facts: Venus is almost as large and dense as Earth; Venus is mostly unfractionated, is as hot, volatile-rich, and mobile internally as Earth, and so no ancient surface can be preserved; Venus lacks plate tectonics, Earth has plumes, so Venus must lose heat mostly by plumes; venusian atmosphere is now hot and dry, so the surface was never appreciably modified by atmospheric or hydrospheric processes. Although only the statements regarding size, density, lack of plate tectonics, and present atmosphere are known to be correct, the other statements being conjectures (most of which are falsified by Anderson, 2006), this chain promptly became dogma. The chain was lengthened, not evaluated, when Magellan imagery was obtained: venusian structures resemble nothing attributed to plumes on Earth [true], but whatever is oberved must be due to endogenic processes [conjecture] so plumes operate uniquely on Venus [!]. This composite chain is accepted in nearly all mainline geologic and geodynamic venusian literature (e.g., Stofan and Smrekar, 2005; Turcotte, 1995). Nikolaeva (1993) was among the very few who continued to argue for impacts after plumology became fashionable.

Atmosphere and Hydrosphere

A recurring theme in this report is that Venus had oceans during much of the early period recorded by its older impact structures. The present highly evolved greenhouse atmosphere is dense (~90 bars), hot (surface T ~450°C), dry (96.5% CO_2, 3.5% N_2, ~250 ppm H_2O, traces of many other gases). So what was the composition and state of the early atmosphere; and could there indeed have been a hydrosphere?

The mainline venusian literature assumes that Venus has had a hot, anhydrous atmosphere and surface throughout the era recorded by everything now exposed. Venus nevertheless must have accreted with abundant water. Although accretion began from local feeding zones in the protoplanetary disk, by about 10^7 years, when the planets had something like half their final masses, eccentricities of orbits of protoplanets in the asteroid belt (components of which are graded Jupiterward in general composition from metallic and stony through hydrous carbonaceous masses to dirty ices) had been so pumped up by Jupiter and protoplanets that they were abundantly accreted to the inner planets until those reached essentially their final sizes before something like 10^8 years had elapsed (Raymond et al., 2006). Much water may also have come in with dust particles (Kulikov et al., 2006). Much water would have been lost to space from impact erosion, from the magma oceans resulting from accretion, and from erosion by violent radiation by the infant Sun, and uncertainties are huge. Among the options are early oceans, which permit explanation of the present atmospheric deuterium/hydrogen ratio of Venus, which is ~120 times that of Earth, as contrasted with the lack of mass fractionation of oxygen and nitrogen isotopes (Kulikov et al., 2006).

Lowlands dominate Venus. The plains are radar-dark, hence smooth-surfaced, and conventionally are assumed to be flood basalts, but lava-flow speculation is countered by the almost total lack of possible sources—volcanoes, dikes, rifts—for eruption of the hypothetical lavas. Evidence that the plains instead are floored by consolidated sediments, thermally metamorphosed by the subsequent greenhouse atmosphere, was presented by Hamilton (2005) and Jones and Pickering (2003). This report emphasizes that thick fill progressively buried old impact structures formed synchronously with deposition. The fill is compacted into many old structures, but the youngest impact structures of the ancient family postdate most of the fill and likely include correlatives of the older "pristine" craters. The surface smoothness of the radar-dark plains, the horizontally laminated character of their material (now hard rock) as imaged by Soviet landers, the compaction of plains materials into and above craters, and the fluidized impact ejecta from many small "pristine" craters in the plains all accord with sedimentary fill. Lowlands are crossed by meandering channels, up to thousands of km long and marked by cut-off meanders, point bars, and deltas, that have semiconstant widths of 1-3 km and depths of ~50 m. The geometry of channels and distributaries resembles that of Earth's submarine turbidite-feeding channels, and turbidites, rather than the conventionally assumed lava flows, may account for lobate patterns on plains surfaces (Jones and Pickering, 2003). However, only magmatic explanations for the channels are advocated in the conventional venusian literature. For example, Oshigami and Namiki (2005) argued for erosion by lavas, and Lang and Hansen (2006) proposed continuous linear sapping from below by lava flowing thousands of km beneath uniformly thin cover—even though these implausible processes cannot account for the continuity and constant dimensions of the channels.

Large tracts ("shield fields") of the plains, including the filled interiors of many old circular structures, are randomly pimpled by perhaps a million small smooth-surfaced cones, typically several km in diameter, <200 m high, and often bearing small crestal craters. These cones commonly are assumed to be of basalt, but they nowhere define rifts or other suggestions of magmatic sources. The cones may be mud volcanoes developed from wet sediments overpressured by top-down heating by the developing greenhouse atmosphere into which the ocean evaporated (Hamilton, 2005). Terrestrial mud volcanoes, “the most important pathway for degassing deeply buried sediments” (Dimitrov, 2002), are similar in morphology and variety to the small venusian shields. The slight deformation recorded by plains wrinkle ridges and reticulate fracture systems ends abruptly against bedrock uplands, and also may be due to atmospheric thermal effects.

Old impact structures are variably smoothed and degraded by erosion, much of it likely submarine, and many impact structures may have formed underwater. Much lowland sediment may have been recycled from local comminuted impact debris, but erosion of uplands presumably also provided much sediment. The general aspect of venusian uplands is of scoured bedrock and etched landforms, with accumulations of sediments in small and large low areas and in perched plains. Integrated upland dendritic drainage systems, and other evidence for major fluvial erosion, have been suggested locally but are not present on a large scale, although poorly integrated stream valleys may be widespread, and braided streams (appropriate for the gentle gradients and high sediment supplies) appear to be present. Perhaps wind erosion was a major denudation agent when the planet rotated faster. Given strong winds and extensive impact pulverization, the dense, corrosive, and perhaps supercritical atmosphere would have been a powerful transport medium, and planar sedimentation would have been favored, whether or not eolian sediment was dumped into standing water. There is no high stillstand shoreline apparent in radar imagery but possible recessional shorelines are preserved in some areas.

PROPERTIES OF VENUS

Venusian and solar system data, independent of interpretation of circular structures, provide no support for the chain of conjectures on which consensus plumological speculations are based. Orbital modeling requires that terrestrial planets formed rapidly (Chambers, 2004; Raymond et al., 2006). Abundant isotopic (e.g., Kleine et al., 2004) and other evidence from the sampled parts—Earth, Moon, and meteorites representing Moon, Mars, and asteroids—of the inner solar system requires that planets fractionated as they accreted. Earth, Moon, and Mars, and hence presumably Venus, were near their final sizes, and internally fractionated, before 4.45 Ga., only ~10^8 years after condensation of the protoplanetary disk began. They have not remained mostly unfractionated as assumed by geochemists since the 1950s and by modern plumologists and venusian specialists. Venus has no magnetic field: the core does not convect, and may be solid. Most of the ^{40}Ar ever generated from Earth's ^{40}K is now in the atmosphere (Anderson, 2006). Venus has only 1/4 as much absolute ^{40}Ar in its atmosphere as does Earth; the simplest explanation is that Venus has only a fraction as much heat-generating potassium, as is expected from its assembly primarily from a feeding zone condensed at higher temperature than was Earth's. Radioactive ^{40}K has a relatively short half life and is now only a minor contributor to terrestrial heat, but it was a major contributor in the young Earth, and Earth's huge heat content is mostly residual from its early history. Current terrestrial dynamic mobility is greatly enhanced by water and CO_2 cycled into the mantle by plate tectonics. Venus lacks plate tectonics and likely has a volatile-poor mantle. Venus is far stiffer that Earth because it is both colder and lower in weakening and melt-enhancing volatiles.

Lithosphere Strength

The great contrast between terrestrial and venusian geoids highlights the dissimilarity between internal properties of the two planets. Earth's topography is supported isostatically by lateral variations in density mostly at lower-crustal and uppermost-mantle depths; topography is almost invisible in the geoid, which reflects density variations, including subducted slabs, deeper in the mantle (Figure 1-A). Venusian topography and geoid (Figures 1-B and 1-C) correlate directly over a broad dimensional range. Venusian topography may be supported by lithosphere far stronger, even over very long periods, than that of Earth (Kaula, 1994), despite the high surface temperature imposed by the greenhouse atmosphere. If the thousands of large circular structures of Venus indeed are primarily of impact origins, as I argue here, then the high-strength option is required.

<<***Figure 1***>>

Popular conjecture nevertheless presumes Venus to be so hot and active that the lithosphere must be weak, and the correlation between geoid and topography is commonly assumed to require instead very thin, even zero thickness, elastic lithosphere and shallow isostatic compensation (e.g., Anderson and Smrekar, 2006); or else dynamic disequilibrium, whereby rising mantle currents push up the uplands, and sinking currents pull down the lowlands, or, oppositely, in an illustration of the lack of constraints in endogenic conjectures, whereby rising currents thin the crust under lowlands, and sinking ones thicken it under uplands (e.g., Johnson and Richards, 2003; Vezolainen et al., 2004). Anderson and Smrekar (2006) derived their postulate of extremely variable venusian lithosphere primarily from the spherical-harmonic gravity field for wavelengths <~700 km, although gravity is very poorly determined at those short wavelengths (Wieczorek, 2007). Most of the topography is commonly regarded as perhaps 0.5 Ga old, so an implausible corollary of these postulates is that the thermal imbalances have been maintained for hundreds of millions of years.

Jurdy and Stoddard (2007) attributed tectonic significance to the specific location of selected venusian coronae (which I regard as impact structures) on a geoid truncated at degree and order 10. As this spherical-harmonic series is both extremely generalized and distorted by artifacts due to the truncation, such attribution is unwarranted; further, there are abundant old circular structures both higher and lower on that invalid geoid.

Mass imbalance. The integrated sum of venusian excess-mass anomalies is expressed by the great-circle heavy line, calculated by C.L. Johnson from the geoid, across Figure 1-C. That this is approximately equatorial is unlikely to be a coincidence. I attribute the topographically high areas to changes in density consequent upon melting by giant impacts, for which an equatorial bias is not expected, and suggest that the mass imbalance reoriented the planet with regard to its spin axis. (Anderson, 2006, proposed such an explanation for the near-equatorial position of the Tharsis upland of Mars.) Braking by the shift may have contributed to slowing venusian rotation. Perhaps the minor surface deformation recorded by venusian rift zones and plains undulations includes byproducts of the shift. (On Earth, spin imbalances are readily accommodated by shallow-plate motions.) The most conspicuous rift intersection on Venus is at Ozza Mons, an uncommonly large "volcano" (to me, an impact-fluidization construct) on the equator, where three rifts meet at near-120° angles, so lithosphere weakening as a byproduct of exothermic events may be indicated. Less regular but similar is the intersection at Theia Mons, which rises from the low, much-modified tessera upland of Beta Regio. (Venusian papers cite these locations to opposite effect, as evidence for control of volcanoes and rifts by plumes.)

Earth's Properties

Although Earth is far more mobile than Venus, widely assumed terrestrial properties and evolution also are overstated in the direction of excess mobility. The global heat loss commonly assumed for Earth, ~44 TW, is ~40% above the measured value integrated for seafloor age, and is based on models that incorporate an erroneously high thermal conductivity of hot oceanic lithosphere (Hofmeister and Criss, 2005) and lack a sound physical basis (Anderson, 2006). Among other properties that require the lower mantle to be vastly less mobile than postulated by plumists are the great decrease of thermal expansivity, and increase of viscosity, with increasing pressure; the high thermal conductivity of the deep mantle [which may even preclude convection]; the probability of irreversible layering; and the likely cause of the deepest-mantle low-seismic-velocity regions in higher iron contents, not higher temperatures (Anderson, 2006). Numerical modelers of plumes do not properly incorporate these parameters.

CIRCLES, CIRCLES, CIRCLES: IMPACT STRUCTURES YOUNG AND OLD

The unearthly landscapes of Venus (Figure 2) show unimodal topography—no plate tectonics—and thousands of circular structures that typically have raised rims that range from a few to 2000 km in inner diameter. The circular structures generally are well exposed in uplands but variably buried in lowlands by fill that accumulated as the structures developed. On Mercury, the Moon, the south half of Mars, and some satellites of Jupiter and Saturn, such rimmed circular structures are known to record bolide impacts. Only on Venus are they widely presumed to be, with the exception of 1000 minimally-modified small craters, of endogenic origins of types unique in the solar system. *None* of the diverse conjectures of endogenic origins in the mainline literature address the consistent impact-compatible morphology and superpositions of the structures.

<<***Figure 2***>>

Many papers convey the erroneous impression that such structures are sparse. The geologic maps by Ivanov and Head (2001, plates 8 and 9) of the north half of the area of Figure 2-A left the many circular structures undiscriminated within hypothetical, and implausible, circumglobal stratigraphic volcanic units such as “densely fractured plains material.” On the other hand, Stofan and Smrekar (2005) recognized about 3/4 of the obvious large structures in this same view (but none of the many small old structures, and not the dozen or so more that can be inferred additionally from topography), and classed them mostly as endogenic coronae. Stofan and Smrekar, like Jurdy and Stoddard (2007), drew corona boundaries far outside the rimmed circles, lumped overlapping or adjacent circles as single coronae, described features in terms that obscure circularity and impact-compatible morphology, and based endogenic conjectures on isolated examples. To me, the circular rims, the basins they commonly enclose, and the cookie-cutter superpositions are the features that should be addressed. Impacts by bolides pancaked or fragmented in the dense atmosphere (see Cochrane et al., 2006, for examples among “pristine” craters) and superimposed impacts provide the general explanation for the many structures that diverge significantly from circularity and which typically show, where well constrained, rims composited of circular arcs..

Some of the many small old circular structures, with rim diameters from ~5 to 100 km, that are within the view of Figure 2-B are shown in Figure 3. Most such small structures are unmentioned in conventional venusian literature. Some of these small structures arguably should be on the “pristine” list because the arbitrary criteria for identification of modified structures as “pristine” admit fewer structures in uplands, where reflectivity contrasts are low, than in lowlands, where they are high.

<<***Figure 3***>>

Size/Frequency Evidence for Impact Origins

The abundance of bolides wandering about the inner solar system falls off exponentially with increasing size, and abundances and sizes of impact craters on airless Moon (Stöffler et al., 2006) and thin-atmosphere Mars (Frey, 2006a) define almost straight lines on log-log plots. Most incoming small venusian bolides are destroyed in the 90-bar atmosphere, and even the largest of the 1000 venusian craters universally accepted as of impact origins do not clearly define such a line (cf. McKinnon et al., 1997). Most bolides capable of making craters even 100-200 km in diameter apparently are destroyed in the dense atmosphere.

The old circular structures that I see as of impact origin do fit straight log size/log frequency lines. Analysis is complicated by the arbitrary omission of the many small old structures, and of the relatively few giant structures, from conventional databases, and by the custom of measuring diameters of larger old structures not to their topographic rims but to arbitrarily greater diameters, but even these biased measurements define straight log/log lines. Stofan et al. (1992) presented a log-log straight line for their early data, derived mostly from structures with rim diameters of ~100-600 km, but dismissed its impact significance, as a coincidence, in favor of plume conjecture with which they could not explain the correlation. Glaze et al. (2002) confirmed the log/log relationship with a larger data set but did not mention its possible impact significance. Vita-Finzi et al. (2005) used a still larger data set, also showed the log-log size distribution to be as required by impact origins, and emphasized, correctly, that this is powerful evidence for such origins.

Young "Pristine" Craters

About 1000 unmodified to moderately modified small rimmed circular structures on Venus are universally accepted as impact craters. The definitive list is maintained by Robert Herrick at www.lpi.usra.edu/research/vc/vchome.html. Only nine of these craters have rimcrest diameters >100 km, and only one, at 270 km, is >200 km. Their geographic distribution is random (Vita-Finzi et al., 2005, fig. 1; Matias and Jurdy, 2005, attach significance to local divergence from randomness of non-robust small samples). The criterion for inclusion is that there can be no doubt as to impact origin. All other circular features are considered endogenic only by default, yet the list is widely accepted (but not by Vita-Finzi et al.) as including all possible impact structures on the planet. Although often termed "pristine", fewer than half of them actually fit that description and preserve sharp topography, radar-bright breccia floor, and unmodified lobate flow-breccia apron (Figure 4-A). Venusian aprons are dominated by ground-hugging lobate debris flows, rather than by ballistic ejecta as on the airless Moon, because of the dense atmosphere and high gravity.

<<***Figure 4***>>

Herrick (2006) emphasized that about 60% of these craters that can be measured accurately are much modified. Many are partly infilled, and their ejecta blankets partly covered, by younger materials, many are breached, some are tilted, and a few are rifted. Herrick assumed the fill and cover to be volcanic, while puzzling over the lack of eruption sites to feed either inside or outside lavas, and did not consider erosion and sedimentation processes. I see the crater fills as sedimentary, in part because most of the rims are unbreached and the fills apparently were derived from the crater walls.

Many "pristine" craters may have formed in shallow water, and many more formed while the plains sediments were still water-rich. Many craters of the older family may be submarine.

Central-peak Lachappelle Crater and peak-ring Barton Crater show two degrees of erosion and of sedimentary burial of interiors, rims, and aprons (Figure 4-B). Like hundreds of the "pristine" craters, they predate thermal wrinkling of plains, hence, in my terms, predate greenhouse top-down metamorphism of plains sediments and formed when the sediments were wet. More deeply buried by thermally-wrinkled plains sediments is doublet Heloise Crater (Figure 4-C). A tilted, breached, and much modified crater that is accorded conventional “pristine” status was shown by Hamilton (2005, fig. 3-C). Herrick (2006) and Matias and Jurdy (2005) referred to other tilted and modified craters of the young family.

Age of “Pristine” Craters

The “pristine” craters commonly are assumed to have formed within the past 0.3, 0.5, 0.7, or 1.5 billion years, the date varying with the modelers, on a planetary surface broadly resurfaced at about that limiting time by volcanotectonic processes with no terrestrial analogues. This age modeling, at its best, integrates estimated numbers and sizes of captured bolides of different types (metallic and stony [but not weak carbonaceous] asteroid fragments, and comets) with estimates for ablation, fragmentation, pancaking, dispersal, and retardation in the dense atmosphere and for crater dimensions produced by surviving bolides and fragments, and then seeks fits to the size-abundance distribution of the observed craters. Korycansky and Zahnle (2005) thus calculated that the observed craters formed within the last 0.73 Ga, and suggested that uncertainties in their assumptions limited the true maximum age to within a factor of two of this calculated value; say, 0.35 to 1.5 Ga; but uncertainties are large and multiplicative, and that small error limit is optimistic. Prior modeling by others (e.g., McKinnon et al., 1997) yielded preferred maximum ages between 0.3 and 0.7 Ga.

As Schultz (1993) recognized, dating ambiguities permit the “pristine” venusian craters to go back to the early history of the planet. Models and observations agree that most small bolides are destroyed in the venusian atmosphere, and a critical factor for modeling is the survival of larger bolides. Almost all objects that now have orbits reaching inside Earth’s orbit and that are capable of generating craters larger than 100 km in diameter on an airless terrestrial planet are comets, dirty iceballs prone to atmospheric destruction (McKinnon et al., 1997; Shoemaker, 1994, 1998). Earth’s thin atmosphere probably produces far more disruption even of stony meteorites than generally appreciated (Bland and Artemieva, 2003), and venusian atmosphere is almost 100 times as dense as Earth’s. There are so few large “pristine” craters on Venus that no statistical use of them is robust, and no straight-line log-log size-frequency relationship can be established to suggest that a size is represented beyond which all bolides survived to generate craters, although the model ages presume that such a limiting size is well within the observed population.

Only craters of the “pristine” family are superimposed on many of the large circular venusian structures for which lunar analogy indicates a minimum age of ~3.85 Ga. More-modified, hence still older, large impact structures are pocked by variably more, up to full saturation, of the older family of structures.

“Pristine” and Older Craters

Many hundreds of examples provide a continuum between small misnamed “pristine” impact craters and the more-degraded structures commonly presumed endogenic This gradation is denied in mainline venusian literature, which is emphatic (e.g., Strom et al., 2005) that the 1000 “pristine” craters are strikingly different from older rimmed circular structures and are the only impact structures on the planet. Nevertheless, several thousand circular structures are similar in size to, or modestly larger than, the 1000 commonly accepted impact structures are present on Venus, but show variably more modification. Some of these are shown in Figure 3, and more are shown now, before proceeding on to the thousands of larger old circular structures. Small and large old structures are of similar limiting ages, as calibrated by degrees of modifications and by superpositions. Nearly all small, old structures, and perhaps three-fourths of the visible large, old structures, are ignored in conventional venusian work.

Ten small craters, only two of which are widely accepted as of impact origins, are shown by Figure 5. The three neighboring same-size craters of Figure 5-B are similar in aspect except for their quite different erosional smearing and sedimentary cover, and perhaps formed simultaneously from three fragments of a bolide disrupted in the atmosphere, **1** having impacted on land, **2** in shallow water, and **3** in deeper water. (Water, erosion, and sedimentation are not considered in conventional venusian work.) Figure 5-C shows four of the older family of structures that are largely buried by, and predate thermal wrinkling of, plains material. The "tick," the venusian term for a minor structural type commonly assumed endogenic, by contrast postdates plains deformation and likely was produced by a bolide that struck solidly lithified subhorizontal strata at a low angle and generated in them shallow thrust faults, convex downrange. The Spider (Shoemaker and Shoemaker, 1996) and Gosses Bluff (Milton et al., 1996) impact structures of Australia, and Upheaval Dome of Utah (Scherler et al., 2006), have similar thrust patterns and record such impacts and targets.

<<***Figure 5***>>

The plains craters of Figure 6 show an age sequence by their superpositions and modifications. The outer part of the apron of large Isabella Crater, an accepted impact structure, is subdued, and this modification, and also the extremely long runout of its southeast lobe, may be products of an impact that was either shallow submarine or that occurred while the sediments were still saturated with water. Such long runout lobes are seen only about plains craters, not about upland ones. Acoustic fluidization may generally account for the runouts (cf. Collins and

Melosh, 2003), but with an assist from contained water.

<<***Figure 6***>>.

The abundant small likely impact structures on Venus that are overlooked in conventional analysis probably much outnumber the 1000 accepted "pristine" structures, so several thousand of those old, small structures are exposed. The distribution of the old structures is not random about the planet, as is that of "pristine" impact structures. The small old structures commonly are present where coronae are exposed, but are mostly lacking on the youngest of the huge circular structures and on the youngest tessera terrains, and also are unseen in many plains areas. This accords with the obviously large age range of tessera, and with the variable burial of plains structures. Large impact structures in the plains are much more likely to print through to the surface, as illustrated here and by Vita-Finzi et al. (2005, fig. 5).

A pseudoperspective view of Aramaiti corona displays, with modest vertical exaggeration, little-modified impact morphology (Figure 7). Aramaiti is the same size as Mead, the largest venusian crater commonly accepted as of impact origin. Aramaiti's circular rim, steep on the inside and apparently stepped down by concentric collapsed terraces, encloses a basin with a peak-ring uplift. The outside of the rim is a gentle ejecta apron with a broad, shallow ring syncline, a low outer rise beyond that, and, as seen in detailed imagery, radial debris-flow lobes. The structure formed late in the depositional history of the surrounding plains, and presumably smoothing of the structure was submarine. Three probable impact craters that bracket Aramaiti in size are shown and described on Figure 8. McDaniel and Hansen (2005) accepted Aramaiti as an impact structure, and noted others of similar morphology; Hansen had long regarded all coronae as endogenic.

<<***Figures 7 and 8***>>

Aramaiti is conventionally assigned an endogenic origin despite its well-preserved impact morphology. Stofan and Smrekar (2005) speculated that Aramaiti formed by delamination of an inward-migrating rim atop a plume, and Grindrod and Hoogenboom (2006) attributed Aramaiti to sinking of the center as a density inversion within the lithosphere was righted. Neither conjecture addressed the remarkable circularity and impact-compatible morphology, or considered an impact origin. Such speculations might reasonably be invoked to explain an isolated example of this type, but not the hundreds with similar morphology.

Grindrod and Hoogenboom (2006, their figs. 1B, 1C, 1D) showed backscatter images and highly exaggerated pseudoperspective views of three of the many Aramaiti-like coronae with rim diameters near 200 km. All have impact-morphology basins, rims, and gentle aprons of radial debris flows, and are seen on inspection to owe their slight elongations and irregularities to superimposed circles and circular arcs: they are products of impacts by pancaked or fragmented bolides. A number of other small craters with impact-compatible morphology can be seen in each of their images—but Grindrod and Hoogenboom considered only endogenic origins.

If the slight deficit of “pristine” craters upon “coronae” calculated by Jurdy and Stoddard (2007, table 1) is real, and not an illusion due to the ambiguous statistics of small samples, then likely explanations lie in the under-reporting of young impacts in bedrock areas, discussed elsewhere in this report, and perhaps also may indicate that submarine impacts like that of Aramaiti Corona continued well into the era of formation of “pristine” craters.

Superimposed Old Impact Structures

Venus displays thousands of old superimposed rimmed circular structures. The morphologically younger take cookie-cutter bites from the older, as required by impact origins. Examples are illustrated by figures in this paper and in Hamilton (2005). Were the structures endogenic, related to subsurface intrusions as per any of the diverse plume and diapir conjectures, the younger would be deformed against the older, which is not observed. Plume advocates evade this powerful evidence by lumping superimposed or neighboring rimmed basins as single coronae. Törmänen et al. (2005) termed 70 examples of superimposed structures "multiple coronae," and attributed them, without mention of their sequences, geometries, and impact morphologies, to endogenic processes. They considered only isolated clusters, and did not discuss regions saturated with such structures.

A crater-saturated plains region, wherein at least 15 craters were superimposed while being progressively buried by accumulating plains material, is shown by Figure 9. All structures, except for two tiny "pristine" craters, are mostly buried, and some are completely buried and are visible only as depressions produced by compaction into them of plains material. This burial and compaction provide strong evidence that venusian lowlands are filled by sediments, not by the basalts of popular assumption. Such burial is well known on Mars (Buczkowski et al., 2005; Frey, 2006b) but has not been considered in the conventional venusian literature even though many "pristine" craters also are partly buried (Figures 4-B and 4-C; Herrick, 2006).

<<***Figure 9***>>

Complex superpositions obvious in radar reflectivity are illustrated by Figures 10, 11, and 12. Those of Figure 12 include giants pocked by an approximately global-average array of "pristine" craters but by little else, and hence formed late in the pre-"pristine" sequences. Other regions saturated by mostly-buried and variably-bombarded craters are illustrated next.

<<***Figures 10, 11, 12***>>

Large Ancient Impact Structures

The old structures of probable impact origin discussed to this point, like those illustrated by

Hamilton (2005), are shown primarily by radar-brightness imagery, although Figure 9 includes an altimetric image. Structures obvious in reflectivity are sparser in lowlands than uplands, which has led to many erroneous statements about abundances (e.g., Jurdy and Stoddard, 2007). Less than 1000 of the large old circular structures, with rimcrests ~100 to 2000 km in diameter where preserved, are recognized, and assigned to unique-to-Venus structural types, in the conventional literature, and these are disproportionately in uplands. Many reports bundle clusters as single features. Several thousand more large structures, in addition to the several thousand overlooked small, old structures discussed previously, are apparent in radar reflectivity and altimetry and yet are disregarded in the conventional literature.

Both the listed and ignored structures are approximately circular, or are fragments of circles preserved in composites of superimposed circles. Many hundreds of the structures retain raised topographic rims enclosing basins, and many of these also retain flanking aprons. Even plume-advocates Stofan and Smrekar (2005) emphasized that the "typical shape for a corona is a depression or rimmed depression"—not an expected product of hypothetical plumes. Erratic chains of volcanoes, such as are cited (I think wrongly) as evidence for terrestrial plumes, are lacking on Venus. What I see as ejecta aprons of classic impact structures—the lobate outer slopes of rimmed structures, as in many of the accompanying figures—commonly are regarded as lava flows erupted from the flanks of volcanoes, despite the lack of rift-zone sources.

Saturation of Lowlands by Large Impact Structures

Much of the venusian lowlands is saturated by thousands of overlapping apparent impact basins, mostly 100-2000 km in rim diameter, that are variably superimposed, degraded, and buried. The large old structures that I attribute to impact commonly are well shown by reflectivity in venusian uplands—but uplands comprise only about 30% of the planet, and much of those uplands consists of tessera plateaus younger than most old impact structures and so lacking their imprint. Only relatively sparse old circular structures commonly are obvious in radar brightness alone in the lowlands that comprise the rest of the surface, and to this is due the common misconception that the structures are sparse in the lowlands. The little-used topographic imagery shows that large parts of these lowlands in fact are saturated by overlapping circular structures. Most of these lowland structures are invisible in reflectivity alone, or show only as discontinuous arcuate rims projecting through the surface, whereas their shapes are revealed in topography because of compaction of plains fill into variably-buried basins formed during the era of sedimentation. My previous report (Hamilton, 2005) said little about these mostly-buried plains structures because I was unaware of how well they often show in altimetry until I read Vita-Finzi et al. (2005).

Paired images of reflectivity and altimetry are shown for a small region by Figure 9, for large regions by Figures 13 and 14, and for a huge region by Figure 15. Most papers accept nothing shown in these figures, save sparse small "pristine" craters that are invisible in Figure 15, and almost so in Figures 13 and 14, as impacts, whereas I see these areas as mostly saturated by large impact structures. Most of the venusian lowlands resembles Figures 13-15, although the clarity of the circular structures in altimetry varies widely with superpositions and obliteration of older by younger structures and with masking by variable thicknesses of sediments. The basinal structures are particularly obscure or sparse near some uplands, which I attribute to thick sedimentation.

Plains saturation by overlapping circular basins, with rims 150-600 km in diameter, is strikingly shown by the topographic image of Figure 13-B. Many distinct circular basins, mostly rimmed, of diverse ages, and cookie-cutter superpositions of younger on older, are displayed by the different depths of surface offset by sediment compaction. The topographic expression apparently is due to compaction of sediments into impact basins that formed intermittently during the era of sedimentation but before its end. The crosses mark centers, to an arbitrary lower level of confidence, of what I see as likely old impact structures. Most of the circular structures are invisible in the backscatter image (13-A), which shows one corona, Ma, with likely impact morphology, plus several other named coronae of indistinct morphology, all of which appear in altimetry to be composite-impact structures. Small, old impact structures are more obscured by burial, and relatively few of them can be seen in this low-resolution altimetry. The tessera remnants here predate some of these plains-saturating structures but are unsaturated by them, hence postdate many.

<<***Figure 13***>>

Simon Tapper first recognized the spectacular basin-revealing topography of the area of Figure 13. His shaded-relief image was published by Vita-Finzi, Howarth, Tapper, and Robinson (2005, fig. 11), who emphasized that the circular structures record impacts. Earlier, Tapper (in Tapper et al., 1998) had gone along with the conventional assumption that these structures are endogenic. Tapper et al. (1998) stated that they identified 228 new coronae from a global survey of "altimetry and synthetic stereo" images; they did not explain how they selected these structures from the thousands displayed, did not mention the impact-indicative overprinting of older by younger structures, and concentrated on fitting the structures into Stofan's classification of endogenic features.

The paired images of Figure 14 show a more-subdued impact-saturated plains region. The incomplete network of low arcuate ridges apparent in reflectivity (**A**) is seen in altimetry (**B**) to mark parts of the rims of overlapping probable-impact structures. At least 50 variably overlapping and overprinted rimmed circular basins, and remnants thereof, mostly buried by plains sediments, are apparent, and have rim diameters >100 km. The areally varying clarity of structures may reflect thicknesses of overlying sediments. Within this area of ~6x10^6 km^2, there are only two small named coronae, Ituana and Clonia, each of which is a doublet crater consisting of two overlapping rimmed-basin circles. Both Ituana basins have central peaks.

<<***Figure 14***>>

Few of the thousands of lowland circular basins, and their remnants, are recorded on standard lists or maps of venusian structures. This is a function of the restrictive definitions of "corona" and other venusian terms, which arbitrarily exclude most circular structures actually present, and of the underuse of topographic information. The often-published claim that circular structures are sparse in the lowlands is false, and the dominant endogenic conjectures that relate uplands and old circular structures are invalid.

Giant Impact Basins.

Four well-preserved giant circular rim-and-basin structures were illustrated, and described in impact terms, by Hamilton (2005). These structures are Artemis (shown at a small scale here in Figure 12), Lakshmi, Heng-O, and Quetzalpetlatl, which have rim-crest diameters of, respectively 2000, 1400, 900, and 800 km. All but Heng-O preserve great debris aprons. These huge structures are assigned widely conflicting speculative endogenic origins, commonly invoking mantle upwellings or plumes (e.g., Bannister and Hansen, 2006), but in other variants invoking downwellings instead, in the mainline literature.

Many older and more modified giant circular structures also are likely of impact origins. A huge region is shown by Figure 15. At this small scale, the midsize impact basins, 100-600 km in rim diameters, such as are shown on Figure 14 (it and Figure 9 are within this region), are visible primarily as incomplete reticulate patterns in the altimetry. The topographic image (15-B) also shows giant quasicircular depressions, 800-2500 km in diameter, whose floors lie 1 km or more below the general level of surrounding lowlands. These, and the similar giant basins throughout other plains regions, comprise the lowest parts of the planetary surface, and are much less obvious in reflectivity (15-A).

<<***Figure 15***>>

I presume these ancient giant basins also to be products of impacts. The structures dimensionally resemble Aitken-South Pole impact basin (rim diameter 2700 km) on the Moon, and Hellas (1800 km) on Mars, though preservation of the venusian structures is poorer, akin to the still older, and mostly buried, giant impact basins on Mars described by Frey (2006a). Midsize basins, like those of Figure 14, saturate much of the area of these great venusian basins.

Conventional venusian literature commonly regards the giant basins as products of circular downwellings (antiplumes), but the unconstrained conjectures vary widely. One of the best defined of these basins is Atalanta, 2300 km in diameter and just north of Figure 15, whose gentle floor lies 1 or 2 km below the broad topographic rim that encloses most of it. Gauthier and Arkani-Hamed (2000) summarized three of the published downwelling conjectures for Atalanta. It “is the result of a young mantle coldspot or an immature mantle downwelling and the lowland is the surface expression prior to thickening of the crust.” Or, “the central depression [is due to] crustal thinning and the surrounding positive topography to crustal thickening” above the downwelling mantle. Or, their own preference, the crust was thickened over the downwelling and initially stood high, but subsequent cooling was accompanied by transformation of the thickest deep crust to dense phases, causing subsidence. Like the diverse *ad hoc* speculations regarding endogenic origins for coronae and other venusian circular structures, none of these mutually incompatible mechanisms has either local constraints or any analogues elsewhere in the solar system—yet an impact explanation, which meets no such obstacles, is not considered.

Large Impact-Melt and Impact-Fluidization Constructs

Broad pancake-like "tessera" plateaus and the (misnamed?) "volcanoes" of Venus probably formed from impact melts and fluidized debris although, like everything else on the planet older than the 1000 "pristine" craters, they conventionally are assigned young endogenic origins. Elkins-Tanton and Hager (2005) modeled extensive magma generation by large impacts. Shock melt can be much augmented by decompression and delayed melts. Neither plateaus nor "volcanoes" have modern terrestrial analogs, but presumably their equivalents were plentiful in the bolide-bombarded early Earth. Perhaps terrestrial Neoarchean Stillwater and Paleoproterozoic Bushveld and Sudbury complexes are eroded remnants of analogous magmatic masses. Among these only Sudbury has yet been proved to be of impact origin, but it shows that impacts can produce voluminous magmatism. Transitions link plateaus and "volcanoes" to impact basins and indicate the huge constructs to also be products of impacts. The best-preserved plateaus and "volcanoes" almost lack superimposed ancient midsize impact structures (coronae, etc.), whereas small remnants, largely buried by plains sediments, are dismembered by large impact structures of the old family. Tesserae and "volcanoes" thus span much of the visible pre-"pristine"-crater history of Venus.

Tessera Plateaus. The least-buried and least-bombarded tessera (or "crustal") plateaus are quasicircular, have diameters of 1000-2500 km, stand several km above surrounding plains, and display abundant structural evidence for thin-skinned spreading. The distinctive surface structures of these giant pancakes record radial outflow, with radial shortening by folding and with surfaces whose slopes decrease exponentially outward, combined with circumferential extension displayed by radial graben (e.g., Hansen et al., 2000). The features commonly are attributed to plumes, although, as for all other venusian structures thought endogenic, popular speculations vary greatly. I (Hamilton, 2005) proposed an impact-melt interpretation: tessera plateaus are igneous complexes crystallized from giant impact-melt lakes that spread sluggishly outward like continental ice sheets. Hansen (2005) also adopted this explanation.

Lakshmi Planum and Ishtar Terra show a tessera plateau to have formed from a giant impact basin (Hamilton, 2005). Lakshmi is a smooth-floored basin with a raised circular rim 1400 km in diameter, pocked only by "pristine" craters. A huge debris apron is preserved about much of its perimeter, and it appears to be a magma-filled impact structure formed at about the end of the pre-"pristine"-crater history. A great tessera pancake spread into the lowlands from broad ruptures in the northeast half of Lakshmi's rim. This pancake is the western of the three tessera plateaus (products of simultaneous great impacts?) that partly flowed together to make the compound Ishtar Terra upland.

All tesserae have their approximate quotas of "pristine" craters, but they vary widely in age relative to accumulation of impact structures of the ancient family. The great icesheet-like plateaus that are preserved whole, only their outer edges apparently being buried beneath plains sediments, are pocked primarily by "pristine" craters, so are similar in age to the youngest of the great rimmed impact basins, including Artemis. Both huge-basin Lakshmi and the western Ishtar tessera impact melt that broke away from it are similarly pocked primarily by "pristine" craters. From these well-preserved giant pancakes, there are all gradations to small, isolated remnants of older complexes, scattered about the planet, mostly buried by plains sediments and variably disrupted by old impact structures. These remnants can be recognized by their distinctive structure. Increments of the gradation in morphology and cratering are shown by figures in this report and in Hamilton (2005). The two plateaus shown at very small scale in Figure 15 carry very few old-family structures. On the other hand, small, low, irregular Saluf and Manatum remnants of a tessera plateau are older than a trio of particularly conspicuous, hence relatively young, nested large impact basins of the old family (Figure 13-B), but postdate the early craters of that region. Tesserae thus formed during at least the latter half or so of the era recorded by the landscape-saturating midsize craters. This era may have lasted hundreds of millions of years; see discussion below. Perhaps much of the crystalline crust of venusian uplands was formed of products of early impact-melt lakes.

"Volcanoes". Broad, low quasicircular domes and cones—up to many hundreds of km in diameter yet commonly only 1 or 2 km high, mostly with single rather than multiple peaks (there are a few doublets), with large, irregular sags, not calderas or vents, at their crests, and lacking rift zones and associated cones and flows—are strewn randomly about the planet. The edifices are popularly termed "volcanoes" and deemed endogenic, but the characteristics just noted distinguish them from modern terrestrial volcanoes and lava fields. Their occurrence relates them to impacts, and I am dubious of the voluminous magmatism implied by the term "volcano". The constructs typically have outer slopes of <0.5°, and upper slopes of only 1° or 2°. These extremely gentle slopes are shown in the conventional literature with extremely exaggerated topographic profiles and pseudoperspective images that make them appear to be great conical or domiform volcanoes. Thus, Basilevsky and Head (2000) presented "perspective views" of a number of "volcanoes" with unmentioned extreme vertical exaggerations such that low edifices, 200-300 km in diameter and only 1 or 2 km high, rising mostly from rimmed basins, appear to be gigantic steep rounded cones 50 or 70 km high.

The occurrence of the "volcanoes" indicates impact origins, whether or not the constructs are properly magmatic. Most are superimposed on large rimmed depressions (and so often are termed "volcano-corona hybrids"). "Volcanoes" and basins obviously are linked, and to me the links are bolide impacts. Some of the “volcanoes” partly overflow their rims. Some of the largest reveal no enclosing rims, and for these I infer overfilling of impact basins. The large, well-preserved “volcanoes” are pocked only by sparse small “pristine” impact craters, but elsewhere tattered remnants of older “volcanoes” protrude through younger cover and are overprinted also by large and small ancient impact structures (Hamilton, 2005).

Also conventionally classed as “volcanoes” or “mons” are subdued structures (e.g., ***1*** of Figure 8) that have rims, basins, and aprons—to me, again, impact structures. Herrick et al., 2005, explained that particular rim-and-basin structure as due to sagging of the broad top of a volcano as a causative mantle plume “died out.”

These edifices may be products of impact-shock fluidization, rather than of impact melts. Their lobate outer flanks commonly are inferred to be lava flows, but these resemble the impact debris-flow aprons of the young “pristine” impact craters agreed upon by all (e.g., Figures 4-6). Formation of large impact structures can neither be tested experimentally nor extrapolated from small-scale experiments, but powerful computers enable modeling. Key to comprehension of complex craters is the duration of shock fluidization and the amount of uplift of temporarily fluidized crater floors, for the fluidized central uplift can shoot far above the pre-impact ground surface and then collapse downward and outward, even overriding the collapsed transient crater rim (Pierazzo and Collins, 2003, fig. 6). The formation of a venusian “volcano” can be visualized as an extremely rapid accompaniment of the impact event, and the broad crestal sags, which do not resemble calderas, as products of rapid spreading of the collapsing debris pile. See Collins and Melosh (2003) for analysis of the mechanism of sustained fluidal behavior of nonmolten material during long-distance motion on gentle slopes. Or perhaps the venusian “volcanoes” formed from mixed fluidized debris and impact melt. The Sudbury igneous complex of Ontario, with its impact breccias atop a fractionated magma lake, might have formed as a Venus-type “volcano.”

Concentric and Radial Features

Many small and midsize venusian circular structures display impact-type central peaks or peak-rings within their basins, as shown by preceding figures. Additionally, many structures show concentric and radial structures outside their rims, and these may record both impact-shock and surficial processes.

Multiring Structures. Many venusian circular structures are multiring. Circular waveforms, outside the rims of the basins, define broad, shallow ring synforms, beyond which are broad, low rises. Such structures characterize many terrestrial impact structures. Craters on Mars and the Moon, where targets consisted of deep impact rubble within which there was little to hold structure, lack such rings.

Concentric deformation related to a large terrestrial impact is shown by the Vredefort structure of South Africa, which has been eroded 7 or 10 km since it formed ~2.02 Ga (e.g., Brink et al., 1997; Grieve and Therriault, 2000; Reimold and Gibson, 1998). Small basal remnants of, and top-down contact metamorphism by, what may have been a huge impact-melt lake are preserved. The target was a thick platform section of Paleoproterozoic and Neoarchean sedimentary and volcanic rocks and underlying older Archean basement. Concentric structures are shown by geologic mapping, and much of the concentricity is apparent on satellite imagery despite the generally low relief, surficial cover, and weathering (Figure 16). Gravity and magnetic maps show low-resolution concentricity. The initial central peak within the crater is now represented by a core, 20 km in radius, of basement rocks, of which the inner part was raised from the deep crust, inside a collar, to an outer radius of 35 km, of vertical to outward-overturned strata. The collar displays close-spaced but irregular concentric structure. Beyond the collar are minor arcuate anticlines, synclines, and faults, and a broad, deep synclinorium with an axis at a radius of ~55 km. Concentricity is incomplete, and relation to the impact structure uncertain, beyond the outer flank, near 75 km, of that synclinorium. No basin rim is preserved. Identified radial structures are irregular.

<<***Figure 16***>>

Chicxulub crater, the Cretaceous-Tertiary-boundary impact structure in Yucatan, is well preserved beneath a cover of Cenozoic sediments, and is known from drilling and geophysical data (Pope et al., 2004). The structure has a peak ring ~80 km in diameter, a crater rim at ~145 km, an outer trough at ~200 km, and a deformation limit at a diameter of ~250 km. Many old venusian circular structures have such dimensions and proportions. The Triassic Manicouagan impact structure of Quebec was developed in Proterozoic gneisses covered thinly by Paleozoic strata, the latter now preserved only (as displaced blocks?) within a circular moat, 60 km in diameter (Grieve and Head, 1983). Lower-crustal rocks are exposed in the central uplift. A sheet of impact melt, with an initial volume likely >500 km^3, covered the central region, except for the central peak, but not the moat. The original crater rim is not preserved. Other terrestrial impact structures also have circular basins outside their rims. Upheaval Dome, Utah (Scherler et al., 2006) is a small-crater example.

Fine-scale Concentric Structure. No terrestrial craters with which I am familiar display the close-spaced concentric fracturing that characterizes parts of some venusian structures; for example, the inner slope of the broad, shallow ring synform just outside the rim of the giant Artemis structure (Hamilton, 2005, fig. 14). Such venusian occurrences are dominantly in scoured bedrock. I have no specific explanation for such fracturing but presume it to be explicable in impact-compatible terms. Anti-impact venusian papers cite circular fracturing as evidence against impacts, but as they present no plausible endogenic explanation this argument is unconvincing. That no such fracturing is visible in craters formed in impact-rubble regoliths on Mercury, Mars, and the Moon indicates that targets of bedrock, not rubble, are required.

Some of the concentric lines about old venusian impact structures may record surficial processes. Many venusian plains structures (e.g., Figure 17) that have impact morphology softened by what was suggested previously to be submarine erosion display abundant concentric features that differ markedly from the Artemis-style circular grooving and perhaps mark wave-cut shorelines in seas shrinking by evaporation. These concentric structures postdate formation of lobate aprons that I regard as impactite flows. Grindrod et al. (2006) noted similar age relationships and assumed endogenic origins, for which, however, they had no plausible explanation..

<<***Figure 17***>>

Radial Structure. Many circular plains structures with general impact morphology show conspicuous radial radar-bright grooves that also may be of surficial origin. The grooves are the subjects of many papers that interpret them as dikes or graben on endogenic volcanoes (e.g., Aittola and Kostama, 2000; Grindrod et al., 2005; Wilson and Head, 2006). Most radial systems are centered on broad, low, gentle mounds that are enclosed within, or overflow, large circular rims that I regard as impact structures, and have radial aprons of lobate debris flows. As emphasized above, these "volcanoes" are broad, low, and gentle, lack calderas, cones, rifts, and composites of superimposed volcanoes, resemble no modern earthly volcanic edifices, and may be products of collapsing impact-fluidized central peaks rather than of magmatism, either exogenic or endogenic. The grooves themselves lack associated volcanic cones.

Grindrod et al. (2005) analyzed the radial grooves of four of these broad, low structures. In their upper reaches, the grooves are valleys, typically several kilometers wide and hundreds of meters deep, with angle-of-repose sides. Both widths and depths decrease downslope. The valleys cannot mark graben, for, as Grindrod et al. emphasized, the required extensions along concentric circles about the structures would be on the order of 100 times too great to be explicable by the very slight doming that might be inferred from inflation models for the very low rises. (Many papers do explain such radial features with doming, perhaps because greatly exaggerated depictions of topography are misleading.) Grindrod et al. explained the features as thick dikes, injected from a central intrusion, although they recognized that no igneous features are associated with the postulated dikes. The hypothetical dike systems resemble nothing on modern Earth: they lack magmatic features; they are vastly too numerous and thick, and require impossibly large circumferential extension given the lack of doming; they neither anastomose nor step *en echelon* as do dikes; and they do not extend beyond the lobate aprons of their host structures. The lobate outer aprons commonly are explained as lava flows from the postulated dikes in those specific places where the grooves reach the lobes, although such lobes are indistinguishable from those elsewhere on the same circular structures where no grooves are present, and from the common lobate aprons that lack such radial lines. Wilson and Head (2006) explained the lack of surface magmatism along purported dikes in terms of magma density that varied precisely with radial distance—an implausible coincidence. Ernst et al. (2001) speculated that such venusian "dikes" require plumes, a *non sequitur* even if dikes are present.

Ninhursag Corona (Figure 18) displays characteristic circular impact features on which are superimposed radial grooves. Its rim encloses a partly filled crater from which protrudes a central peak, and a large apron of radial debris flows slopes very gently outward from the rim. The radial grooves decrease in abundance outward almost to the limit of that apron but nowhere extend beyond it. Although many of the grooves look on the backscatter image as though they cross the rim from the enclosed depression, the position of the inner edge of the rim appears in altimetry to be inside the innermost concentric features on the backscatter image. (See profile, vertical exaggeration ~70:1, by Jurdy and Stoddard, 2007, fig. 7; slopes appear gentle even displayed with this great distortion.) The grooves are oriented down the extremely gentle slope, show no dendritic pattern suggestive of stream gullies, and lack features suggestive of igneous dikes. The grooves may be flow lines and channels left by catastrophically flowing fluidized impact debris. The subdued character of the debris lobes and the concentric etching on the upper outer slopes accord with a submarine origin for the complex.

<<***Figure 18***>>

Radial systems of radar-bright lines are common on venus "volcanoes," although most are less regular than that of Figure 18. An example, with a suggested mode of impact debris-flow formation in the caption, is shown by Figure 19. For an endogenic explanation of the same structure, illustrated with topographic profiles in which the slopes of <1° are exaggerated 50:1 and 100:1, see Aittola and Kostama (2002) and Kostama and Aittola (2003).

<<***Figure 19***>>

Anti-Impact Arguments

Thousands of old venusian circular structures have the general morphology expected of impact craters—basins enclosed by circular rims that, in the better-preserved examples, are still surrounded by lobate debris aprons, and that display cookie-cutter superpositions. None of the hundreds of papers advocating endogenic origins address these features. Conventional papers assume the structures to be endogenic, and seek hypothetical mechanisms that might produce isolated examples as cross sections, not as circles. As noted previously, the spectacular impact morphology shown by Figure 7 was assigned two convoluted and incompatible endogenic origins in two recent papers, neither of which mentioned the impact option. Papers argue unconstrained endogenic speculations at length, and the few that mention the impact option dismiss it without meaningful discussion. Among the rare discussions is that by Jurdy and Stoddard (2007, in this volume).

The vast and continuous size range of old circular structures, which display impact-compatible morphology throughout a range of topographic-rim diameters from ~5 to 2500 km, defies explanation by endogenic mechanisms. The statement by Stofan and Smrekar (2005) that "the narrow size range and distribution of coronae are inconsistent with an impact origin," and similar statements by Jurdy and Stoddard (2007), reflect arbitrary selections, as "coronae," of a small sample of circular structures and omission from consideration of the thousands of small structures (e.g., Figure 3), the dozens of giant ones (e.g., Figure 12), and even most of the midsize structures (e.g., Figures 13 and 14), because they do not fit assumed endogenic concepts. Further, Stofan and Smrekar, and Jurdy and Stoddard, measure diameters to the outermost recognized concentric features, or to irregular boundaries somewhere else outside the rims, or to boundaries outside groups of circular structures, rather than to circular topographic rims as is done for "pristine" structures, and thus approximately double diameters of structures they do include. Even as thus limited in size range and measured inconsistently, the log size/log frequency distribution of "coronae" yields approximately a straight line, as expected for impact explanations (references cited earlier).

A misunderstood uneven areal distribution of the old structures was cited by Jurdy and Stoddard (2007) as evidence against impact. This misconception is another expression of inclusion of only a small, biased sample of perhaps 5% of the structures at issue, selected because they fit an arbitrary standard of conspicuous visibility that excludes the great majority of lowland structures, perhaps half of upland structures, and nearly all small, old structures in both settings. Elaborate statistical manipulation of this sample is irrelevant to the debate. Truly uneven distribution does characterize uplands, much of which consists of huge impact-melt constructs, tesserae, that postdate most of the older impact structures, but old lowlands and uplands both are saturated with circular structures.

Jurdy and Stoddard (2007) cite the lack of structures transitional in size and character between young and old families as evidence against impact origins, but precisely such transitional structures in fact are conspicuous throughout Venus, as this paper shows. At least half of the "pristine" craters are substantially to severely modified, and the modification series continues throughout the older structures. The conspicuous old structures are larger to vastly larger than the young ones, but there are thousands of small old structures also. I looked at about one-tenth of the Jurdy and Stoddard BAT study region, the Beta Regio area from 10° to 40°N and 265 to 305°E, and found, in addition to the standard-list "pristine" craters, about 20 small structures of transitional aspect, plus, in addition to the "coronae" they showed, another 70 more-modified small and midsize structures that I see as probable to possible impact features. This sub-region is dominated by middle-aged tesserae on which relatively few pre-"pristine" structures are to be expected.

Jurdy and Stoddard (2007) draw elongate, irregular blobs far outside the rimmed circular structures at issue, or outside groups of neighboring structures, term the blobs "coronae," and claim the elongations of the blobs to be incompatible with impacts. Their own figure 4 shows the relevant structures to be dominantly circular, so the exercise has no bearing on the analysis. They also mis-cite the irregularities in noisy, artifact-ridden low-resolution altimetric profiles, presented with erratic vertical exaggerations between 65:1 to 160:1, as evidence against impacts.

The arbitrary criteria for identification of modified structures as "pristine" admit fewer structures in uplands, where reflectivity contrasts are low, than in lowlands, where they are high.

This subjective factor can account for the slight deficit (if it be statistically valid) near coronae of standard-list "pristine" craters claimed by Matias and Jurdy (2005).

Many dismissals of impact origins are in the form of assertions of the assumptions required by venusian plumology: Venus is too active internally to preserve ancient features, it was resurfaced recently by plumes, its landscape has never been modified by erosion and sedimentation, etc. These unvalidated assumptions are at issue and are not proper arguments. Conversely, if the old circular structures indeed are of impact origins, these assumptions are disproved.

If viable anti-impact arguments exist, I am unaware of them.

EVOLUTION OF VENUS

There are several thousand large circular structures on Venus for which the obvious explanation is formation by bolide impacts, and yet the reader will find no objective discussion of this in the conventional venusian literature. If my analysis is correct that the abundant old rimmed circular structures on Venus indeed are impact structures, then analogy with dated lunar materials requires that they mostly date from early planetary history. At issue is not a mere pushing of venusian "resurfacing" a bit farther back in time. Venus retains a landscape shaped by impacts recording the tail end of main planetary accretion, complicated by effects of a transient hydrosphere and a runaway greenhouse atmosphere.

Age of Surface

The oldest radar-visible features in venusian uplands may be as old as 4.4 Ga. Venus has been too immobile internally—too cold, too low in volatiles, or both—for its inner workings to have since much affected its visible surface. Even the minor endogenic rifting and warping it does display may be due to repositioning stresses. Venus is more a big sister to Mars than a twin to Earth

The thousands of impact structures on Venus that are older than the 1000 accepted "pristine" craters can be assigned a general minimum age by analogy with Imbrium, the youngest large impact basin on the nearside of the Moon, which formed at 3.85 Ga (Stöffler et al., 2006) or 3.91 Ga (Gnos et al., 2004). Among other large lunar impact structures, only undated Orientale basin, mostly on the lunar farside, may be younger. Imbrium and Orientale are pocked only by small impact craters, analogous to venusian "pristine" craters although vastly more numerous on the airless Moon. Imbrium has a rim diameter of 1200 km, Orientale 900 km, but their bolides would have made smaller basins on higher-gravity Venus. Dated rocks from the Moon go back to 4.45 or 4.50 Ga, so the Moon had most of its present size by that early time. So did Earth, for terrestrial crustal zircons, recycled into younger rocks, as old as 4.43 Ga are known. Subsequent bolides gardened the surfaces but added relatively little mass.

A great bombardment of large bolides, from about 3.95 to 3.85 Ga, is widely assumed to have affected the Moon, hence necessarily also Earth and Venus. The bombardment was inferred by Dalrymple and Ryder (1993) from the Gaussian scatter of Ar/Ar dates of many shock-melted glasses in impact breccias collected on Apollo missions. The postulate of a late heavy bombardment suffers from the implausibility of parking numerous large bolides somewhere in the inner solar system for hundreds of millions of years until they are released at ~3.9 Ga, or otherwise suddenly deriving them; and it is incompatible with photogeologic evidence (Baldwin, 2006). Haskin et al. (1998) showed that the glasses used by Dalrymple and Ryder could have come from the vast Imbrium ejecta blanket, and thus that the dates may record only the Imbrium event, their spread representing diffusion and analytical scatter. Stöffler, Ryder, et al. (2006) agreed that evidence for a late bombardment now appears to be lacking (but Norman et al., 2006, disagreed). Much-smaller bolides have since continued to impact the Moon, but there may have been no concentrated terminal bombardment. Lunar zircon dates, from granophyres and gabbros, decrease exponentially in abundance with decreasing age from 4.3 to 3.9 Ga (Meyer et al., 1996). I suggest that these granophyres and gabbros were produced in impact-melt lakes and represent the exponential decline of accretion intensity after the Moon reached essentially its final size, as expected from orbital considerations. In these terms, 3.9 Ga approximately dates the end of the tail of accretion of large bolides in the inner solar system, including Venus.

The largest well-preserved impact basins on Venus (Artemis, Figure 12; and Lakshmi, Heng-O, and Quetzalpetlatl, all illustrated and discussed by Hamilton, 2005) are pocked mostly by craters of the "pristine" family, hence formed late in the era recorded by the old impact structures. I presume these large structures (and also the similarly-pocked youngest of the tessera plateaus) to correlate approximately with Imbrium, ~3.9 Ga. The equally large quasicircular depressions of Figure 15 are markedly older, for the fill in at least some of them is saturated by old midsize craters. Frey (2006b) evaluated the size-frequency distribution of analogous craters superimposed on similar giant impact basins on Mars in terms of an accretionary model, and deduced a minimum age of 4.26 Ga for those basins. As Earth, Moon, Mars, and presumably Venus had almost their present sizes before 4.4 Ga, I presume that the venusian impact landscape may well reach back to 4.4 Ga.

Crust of Venus During Late Accretion

Mars and the Moon had mostly rubble surfaces, gardened by impact upon impact, during late main accretion. Many more venusian craters of the old family may have formed on solid crust rather than regolith. This would account for the bedrock-target aspect of upland craters, and the clean aspect of the best-displayed old lowland-saturating ones (e.g., Figure 13). Small remnants of tessera plateaus widely show as basement, so the oldest visible crust might have consisted of the products of impact melts, rather than of still-older magma-ocean fractionates. The surface of Venus was largely stabilized before 3.9 Ga; judging from the saturation of much of its surface by midsize and giant impact structures, and likely long before. Venus nevertheless must have retained plentiful internal heat far longer than did small, fast-cooling Mars and the Moon, and its thermal history awaits evaluation in terms of new concepts.

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FIGURE CAPTIONS

Figure 1. Contrasted geoids show Earth to have thin, weak lithosphere, and Venus to have strong, thick lithosphere and hence far less internal mobility despite high surface temperature. **A**, Terrestrial geoid, 10 meter contours, blue and pink low, green-yellow-brown high. Topography is mostly compensated isostatically at shallow depths, and shows almost no correlation with geoid. **B**, Venusian topography and **C**, geoid correlate directly over a broad range of wavelengths because lithosphere is far stiffer than Earth's and supports topography with strength rather than isostasy. Geoid height, **C**, shown by 10 meter contours, 0 not shown, red positive,

blue negative; spherical harmonic degrees 2-30 are fully retained but, because reliability falls off at higher degrees, a Gaussian roll-off is applied to degrees 30-60. Venus maps are centered on the equator and longitude 180°. Centers of arbitrarily selected backscatter-identified coronae, which do not include most large lowland circular structures here regarded as of impact origin, are marked by dots in **B** and **C**. **A** provided by David Sandwell, and **B** and **C** by Catherine Johnson, who supplied the topographic scale, corrected from that published by Johnson and Richards (2003).

Figure 2. Regions mostly saturated with old circular impact structures that, in these backscatter images, are more obvious in highlands than in variably-buried lowlands. The better-preserved structures have raised rims that enclose basins and are surrounded by debris aprons; some are multiring. **A**, top: of 11 small "pristine" craters in this area, the only one obvious at this scale is the radar-bright tailed object in central part of dark area near northwest corner of area. All other circular structures are commonly considered endogenic, formed by plumes and diapirs. **B**, bottom: about half of the large structures visible are conventionally termed coronae and paterae, either individually or as arbitrary aggregates, and regarded as endogenic, whereas the other half are overlooked. Of the many small circular structures within the view, but mostly inconspicuous at this scale, only about 1/3 (e.g., bottom edge, left of center) are classed as "pristine" craters and commonly are accepted as impacts. Some of the small circular structures here regarded as older impacts are shown in Figure 3. Although the Parga rift zone crosses the area from upper left to right center, most structures within it retain circular shapes.

Figure 3. Small, old probable-impact circular structures within the area of Figure 2-B. Upper left image: two of these small structures retain exposed rims; northern one appears to be a "tick",

with thrust-faulted margins indicative of oblique impact into consolidated sediments. Left center image: two small structures retain exposed rims; west one is a doublet. Lower left image: northern structure retains exposed rim and some of apron; rim of southern structure is exposed in west but likely mostly buried by sediment in east; both structures are within an older impact structure obvious in Figure 2-B. Upper right image: pristine Elza Crater is superimposed on a buried old crater into which covering sediments are compacted. Right center image: a small compound crater (near northeast corner) has an exposed rim surrounding a closed depression; large crater (Nordenflycht Patera, left) is mostly buried, but compaction of sediments leaves a large closed depression; the north part of a more deeply buried large crater shows in south. Lower right image: large mostly-buried crater (Hervor Corona, right) is cut by three nested craters (from almost simultaneous impacts by fragments of a single bolide?), of which **1** cuts **2** which cuts **3**; in northwest, **4** cuts **5**, rims of both being partly exposed. Only Elza Crater among all of these structures is conventionally assigned an impact origin.

Figure 4. Modified structures universally accepted as impacts. **A**: Aurelie Crater is one of only ~ 40% of the accepted structures that warrant the designation "pristine." It has sharp topography, radar-bright breccia floor, central peak, and apron of lobate debris-flow breccias. **B**: Central-peak Lachapelle Crater (lower left) is partly filled by radar-dark sediments, derived from the walls, and its ejecta apron was partly eroded and partly buried by plains sediments before those sediments were thermally wrinkled. Peak-ring Barton Crater is more degraded, its interior more deeply filled, and its apron more buried by plains material. **C**: Double-impact Heloise Crater is breached and almost buried by plains sediments, and predates their thermal wrinkling.

Figure 5. Small circular structures, old and new, among which only Browning and Yakyt

Craters are commonly accepted as impacts. **A**: Small breached crater, mostly buried by plains sediments, is conventionally classed as endogenic. Compare with “pristine” Heloise Crater, Figure 4-C. **B**: Variable degradation of three initially similar craters. **1**, Sediment partly fills, and laps on to apron, of Browning Crater. **2**, erosion-smeared impact structure was partly buried by plains sediments before thermal wrinkling; retains closed crater. **3**, similar, but still more subdued, structure largely buried by plains sediments. Impact, erosion, and burial of **2** and **3** may have been submarine. **C**: Five small likely impact structures are marked by question marks. The northern four of these are largely buried by, and predate the thermal deformation of, plains sediments, and may record submarine impacts. See text for discussion of the “tick.” Area extends from 2° to 3°N, and from 169.0° to 170.5°E.

Figure 6. Variably preserved impact craters, numbered in inferred order of increasing age. **1**, tiny Cohn Crater. **2**, cluster of four tiny likely-simultaneous craters. **3**, Isabella Crater, second-largest generally accepted impact crater on Venus, rimcrest diameter 175 km (note imperfect circularity), crater filled by dark sediment; outer parts of lobate debris apron and of long runout to southeast are smeared and subdued, so may have been shallow-marine. **4**, deep crater, topographic rim 60 km in diameter, preserves debris apron; partly covered by Isabella debris flows. **5**, tiny Alimat Crater (left of number), buried except for rim. **6** and **7**, craters with rims ~50 km in diameter. **8**, mostly-buried crater, rim ~200 km. **9**, rimmed depression compacted above 200-km crater; Isabella debris flows were deflected by rim. **1**, **3**, and **5** are commonly accepted as “pristine;” **4** and **8** are classed as endogenic coronae; and the others are overlooked. Other more-modified craters can be inferred on detailed imagery..

Figure 7. Northeastward pseudoperspective view of Aramaiti Corona (26°S, 82°E), showing impact morphology typical of well-preserved circular structures conventionally classed as endogenic. Rimcrest is 270 km in diameter, and its steep inner slope appears to be terraced by slumps. Crater has central peak-ring uplift. Smoothed and darkened conical ejecta apron slopes into ring syncline. Broad outer rise, outside diameter 400 km, preserves faint debris-flow lobes. Impact and softening of morphology may have been submarine. Figure prepared by Trent Hare, U.S. Geological Survey, by draping radar-brightness image on topographic model with vertical exaggeration of 3:1.

Figure 8. Three modified probable impact craters. ***1*** has subdued rim, central peak, and well-preserved lobate ejecta apron that flowed into ***2***, floor and rim of which are nearly circular despite lopsided backscatter appearance. Most of rim of large crater ***3*** is outside view and is buried. Conventional interpretation: ***1*** is endogenic volcano, Chloris Mons; ***2*** and ***3*** are endogenic coronae. (Small feature ***4*** does not appear at high resolution to be a crater.)

Figure 9. Progressive burial, by compacted plains sediments, of impact structures that saturate region from 19° to 27°N and 95° to 100°E. **A**, radar backscatter; **B**, altimetry, relief ~1 km, white is high, black is low. Impact structures visible in **A** are numbered in inferred order of age. **1** and **2** (right of number) are small “pristine” Horner and Criss Craters. **3**, crater, rim diameter 70 km. **4**, subdued crater, 180 km rim. **5**, **6**, and **7**, probable craters, each ~50 km in diameter. **8** and **9**, 200 km craters; **10**, 180 km; **9** and **10** are mostly buried. **11**, compaction depression over buried crater ~200 km in diameter. Additional buried structures revealed by compaction can be inferred in **B**; **X**s mark shallow depressions over possible buried craters, and **Y**s mark possible

buried rims. In all, 13 impact craters older than "pristine" **1** and **2** are inferred. Of these, **4**, **8**, and **10** are conventionally classed as endogenic coronae, and the other 10 are disregarded.

Figure 10. Terrain saturated with eroded superimposed impact craters, numbered in inferred order of increasing age. **1**, Darline Crater, rim diameter 13 km. **2**, slightly degraded crater with 15 km rim. **3**, subdued 30 km crater. **4**, more-subdued 22 km crater. **5** and **6**, and several other circular arcs not marked, may be remnants of other craters. **7**, much-degraded crater, rim diameter ~80 km. **8**, much-degraded crater, rimcrest ~130 km. Conventional analysis: **1** is "pristine," **2** is ignored, and **3** through **8** are lumped as Beruth Corona and assumed to have a unified endogenic origin.

Figure 11. Cookie-cutter superpositions of impact craters. Crater **1** cuts larger **2**, which cuts much larger **3**. A possible 30-km crater that also cuts **3** is marked by **X**. Conventional interpretation: the craters collectively comprise Acrea Corona, and nothing in view relates to impact.

Figure 12. Southwestward "view" over large superimposed impact basins toward horizon at 90°E of venusian hemisphere. Largest well-preserved circular basin on Venus is Artemis (top center). Topographic rim, which is gentle outside and steeper inside, is at inner edge of radar-bright ring and is 2000 km in diameter. Axis of broad, shallow ring syncline is near outer part of bright ring; low outer rise and broad apron extend far to left from there. Everything visible at this scale, including large and small circles, is commonly considered endogenic.

Figure 13. Paired radar reflectivity (**A**) and altimetric (**B**) images of a crater-saturated region of plains and tessera remnants. In **A**, remnants of tessera are seen to project through plains sediments, which host a few coronae that mostly have indistinct morphology. Xs mark the two largest and most conspicuous of the 14 small, young impact structures conventionally recognized in this area. The altimetric grayscale grades from white, the highest parts of the map-area, to black, the lowest; total relief is ~4 km, but most of the region is within a 2-km range. The large and variably superimposed dark circular depressions (crosses) are inferred to mark impact basins, formed while plains sediments were being deposited, that were buried to different depths, and into which the sediments were compacted.

Figure 14. Radar-reflectivity (**A**) and altimetric (**B**) images of a plains region saturated with large, old, mostly-buried impact structures. Parts of rims stand above plains sediments as low arcuate ridges. Topography shows compaction of sediments into basins, and a complex array of superimposed likely impact structures, of which those apparent at this scale mostly have rims 100-400 km in diameter. Almost all of these structures are overlooked in conventional work, and only two are named. Ituana Corona (above label) and small Clonia Corona (left of label but inconspicuous at this scale) both appear on detailed imagery to be doublet impact craters. Caccini Crater (below label; rim 38 km in diameter) is the largest of the seven small accepted "pristine" impact craters in this view.

Figure 15. Radar-reflectivity (**A**) and altimetric (**B**) images of a huge region, much of which is saturated with probable impact structures, with rim diameters up to ~600 km, that show primarily as reticulations in the altimetry. Giant quasicircular depressions, 800-2000 km in diameter, are emphasized (dark) by the topography, wheras their discontinuous rims are shown

as arcuate remnants in the reflectivity, and are inferred to be ancient impact basins. The two large quasicircular plateaus, bright in both images, in the southwest are tessera plateaus. Ganis rift and ridge, trending southeast and south below right center and shown best in the topography, are superimposed on an impact-saturated landscape.

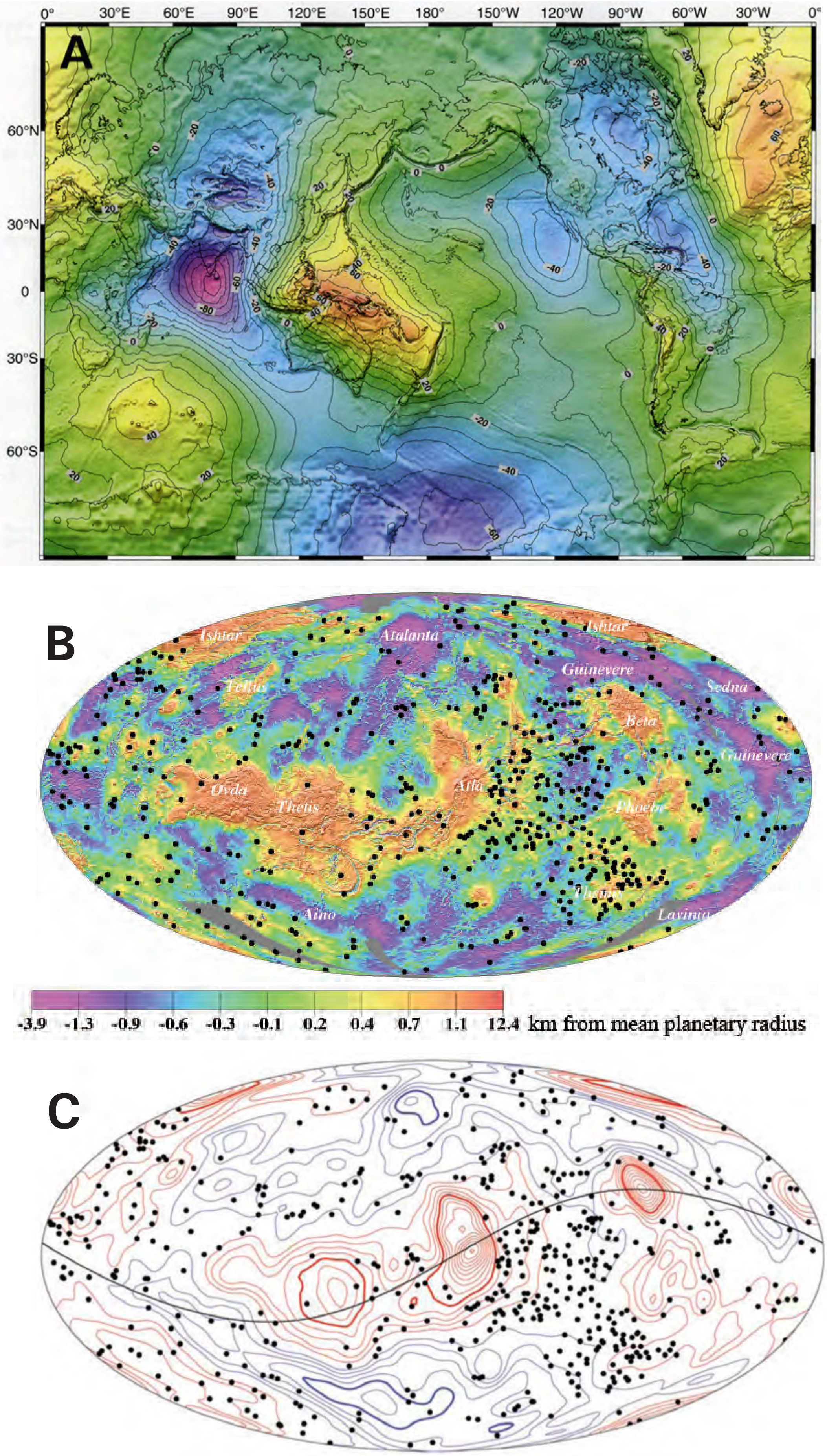
Figure 16. Northwest part of deeply eroded Paleoproterozoic Vredefort impact structure, South Africa, which displays much concentric structure despite deep erosion and widespread surficial deposits. Around the central uplift of basement rocks is a collar of steep to overturned Neoarchean and Paleoproterozoic stratified rocks. A broad syncline within the major synclinorium is visible at left center, and other concentric elements are visible far beyond the collar. Landsat image provided by Frank Wieland.

Figure 17. Plains impact structure (Serova Patera) with concentric rings that perhaps are wavecut shorelines from an evaporating sea. Structure has impact morphology—a circular rim enclosing a crater, and a flanking apron of lobate debris flows. The non-intersecting radar-bright lines that form concentric arcs about, particularly, the higher part of the structure appear to be following contours. The arcs are most conspicuous on the north-facing parts of both outer and inner slopes. Conventional explanation: endogenic structure, which was never in contact with water.

Figure 18. Ninhursag Corona shows impact morphology. The radar-bright rim stands <2 km above the lowest part of the surrounding plains, and encloses a basin, partly filled by radar-dark sediment, from which rises a small peak that is lower than the rim. Radial structure may relate to impact-debris flow, as discussed in text. Conventional explanation: plume plus volcanism.

Figure 19. Mbokumu Mons has a broad, low radially-streaked mound (dark) within a subdued impact-crater rim (light) that is surrounded by an apron of radial debris flows. Relief from top of mound to outer edge of apron is only 1.0-1.5 km, and overall slope is ~0.5°. Radial lines (light) go from crest of mound, cross much of rim, and give way to debris lobes. Suggestion: part of debris apron was sloughed off collapsing impact-fluidized central peak, almost instantaneously after impact. Conventional explanation: endogenic volcanism.

Figure 1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Thetis
Atla
Phoebe
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Lavinia
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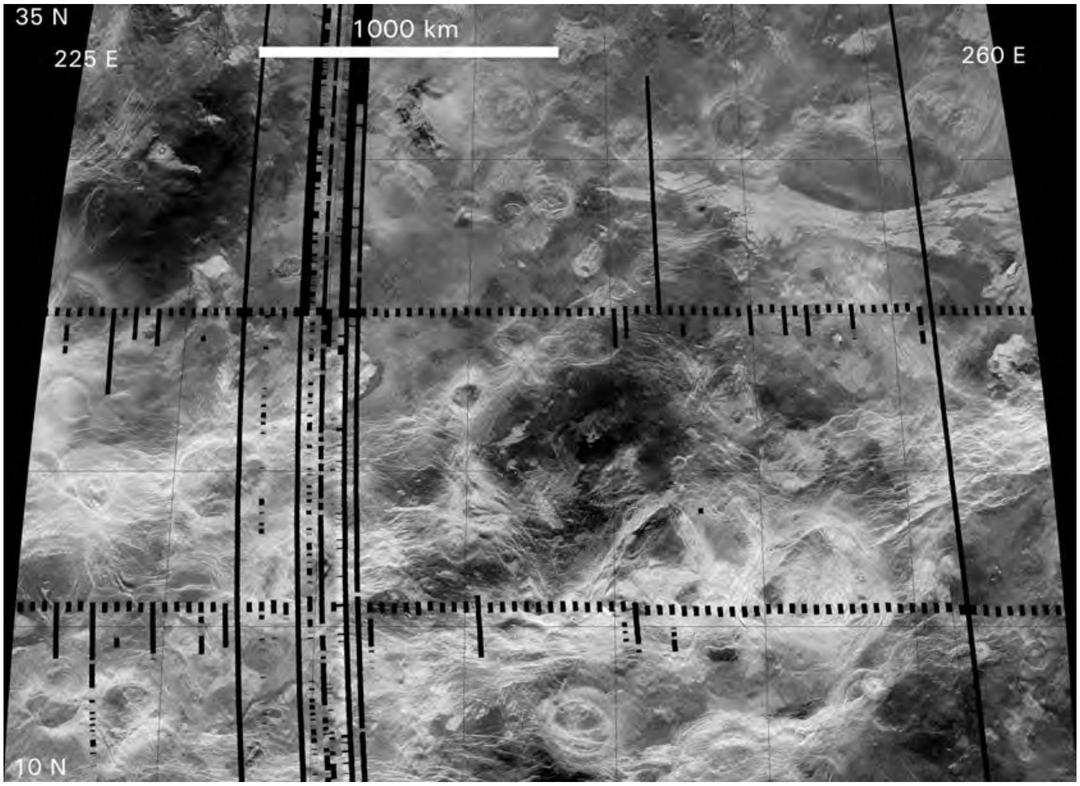

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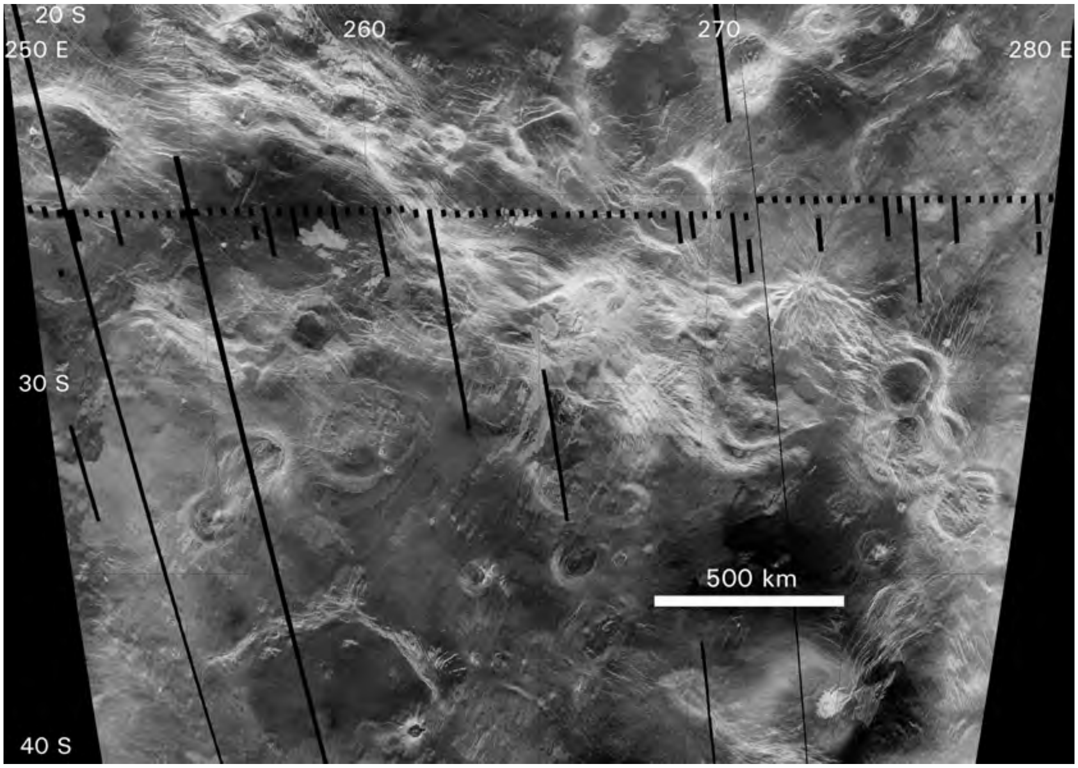

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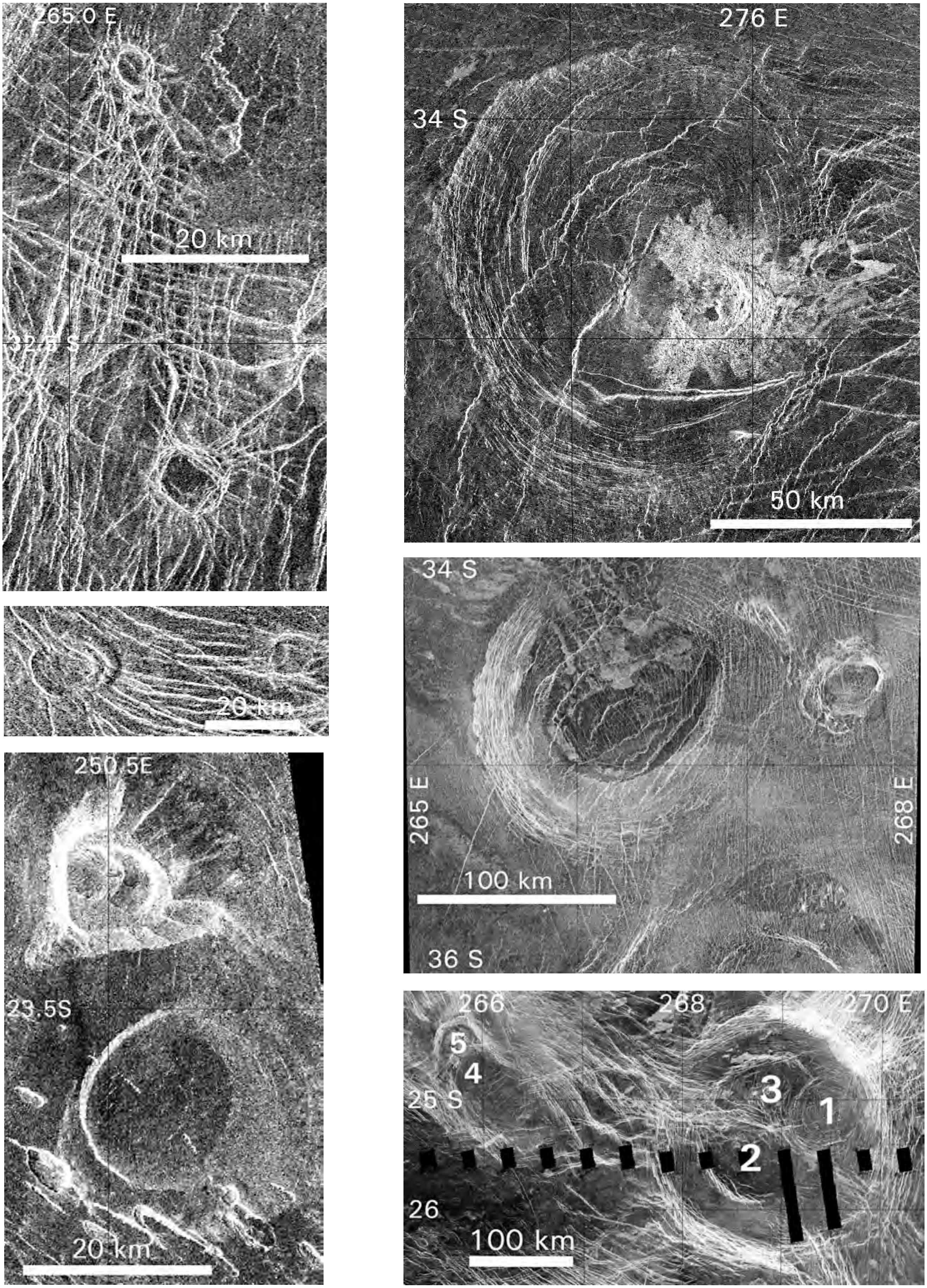
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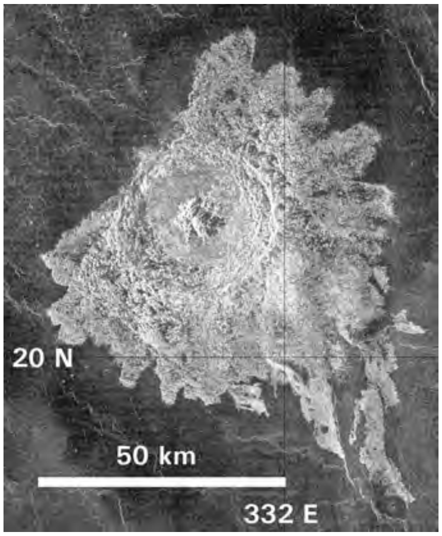
Figure 3



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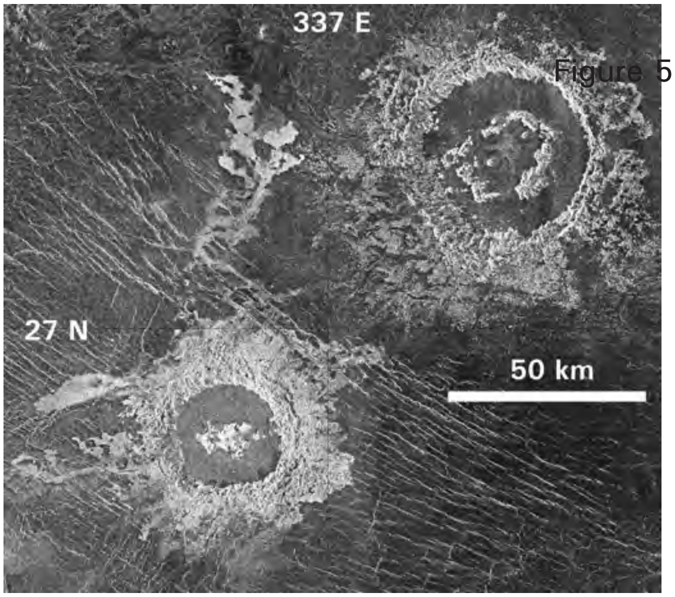
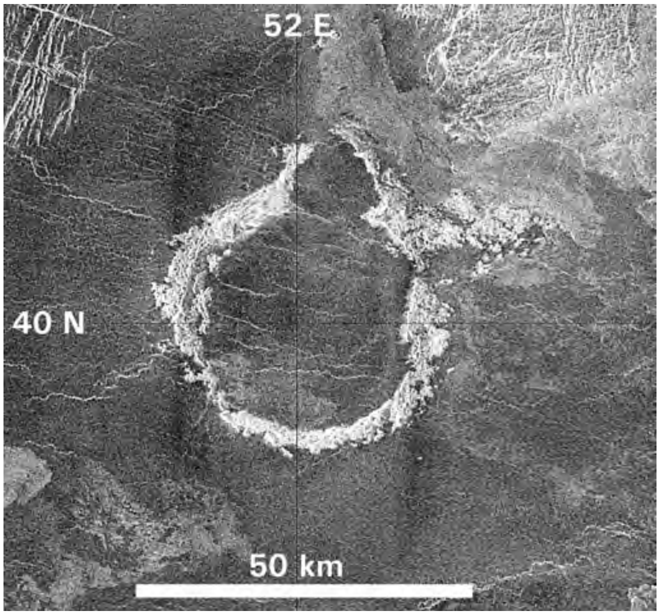


Figure 5

Figure 4-B



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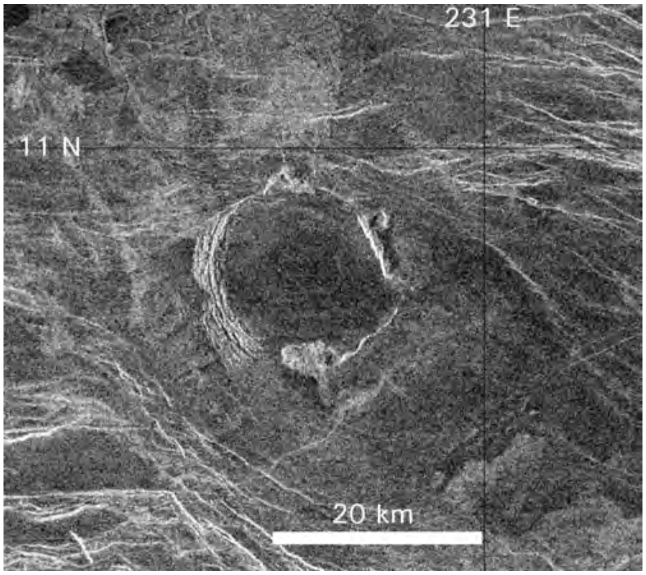

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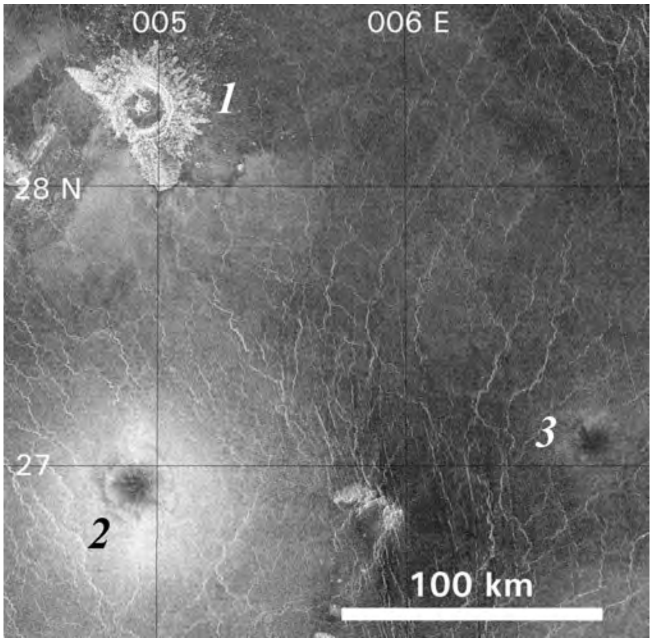

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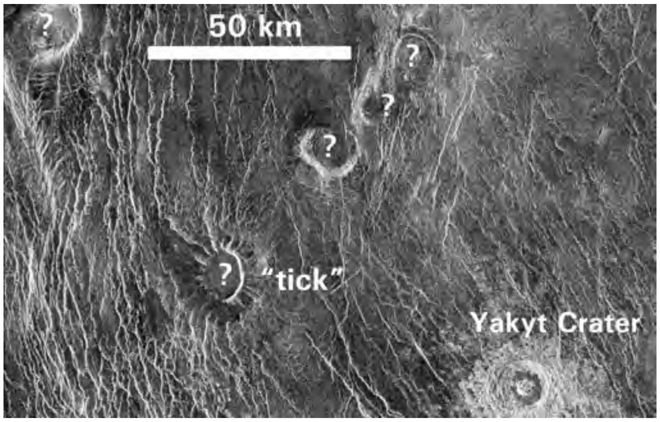

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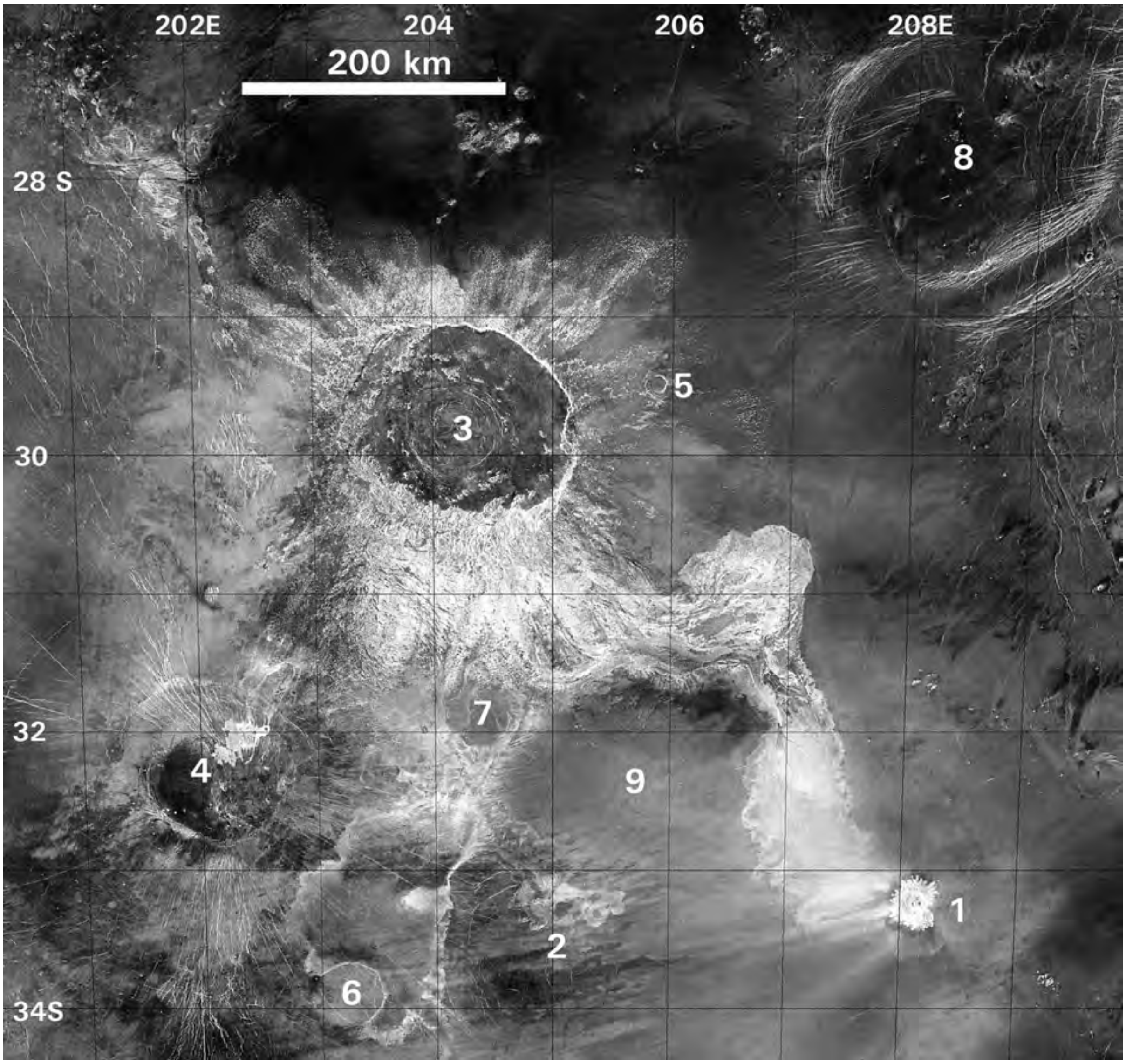

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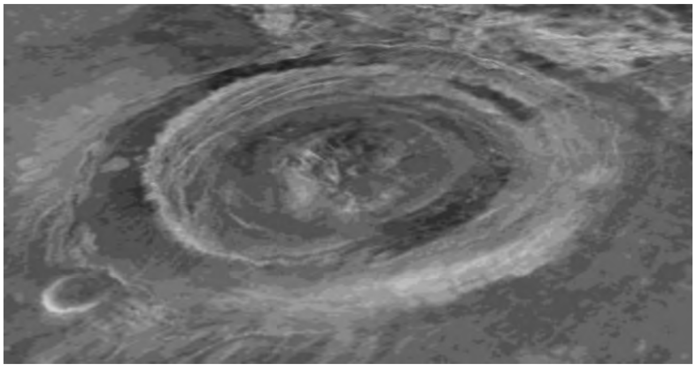

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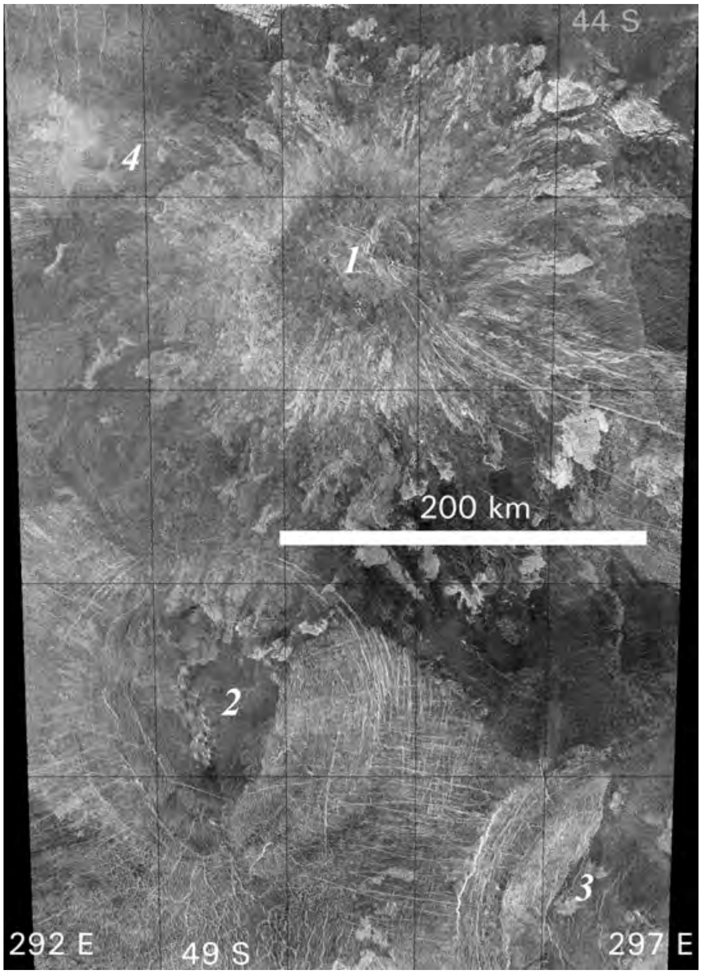

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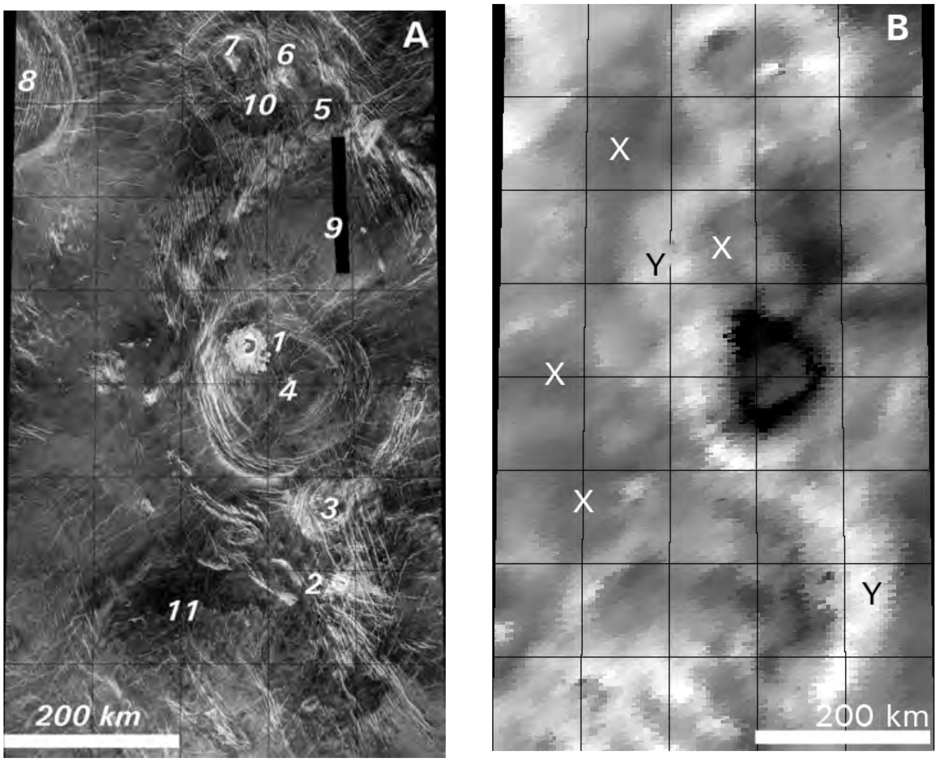

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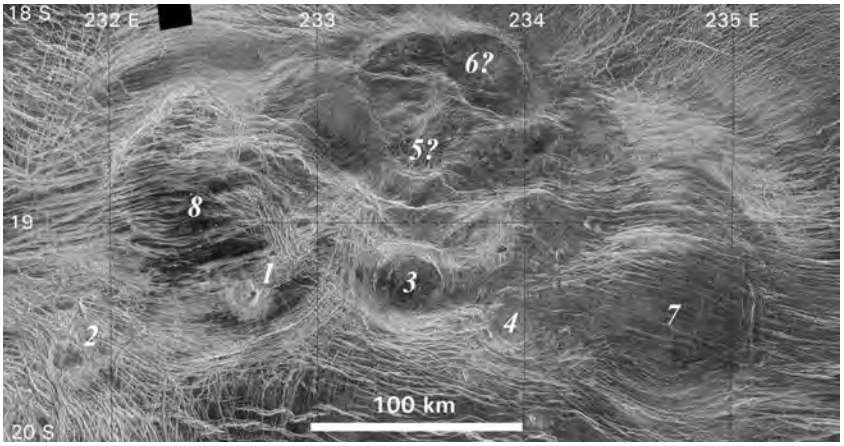

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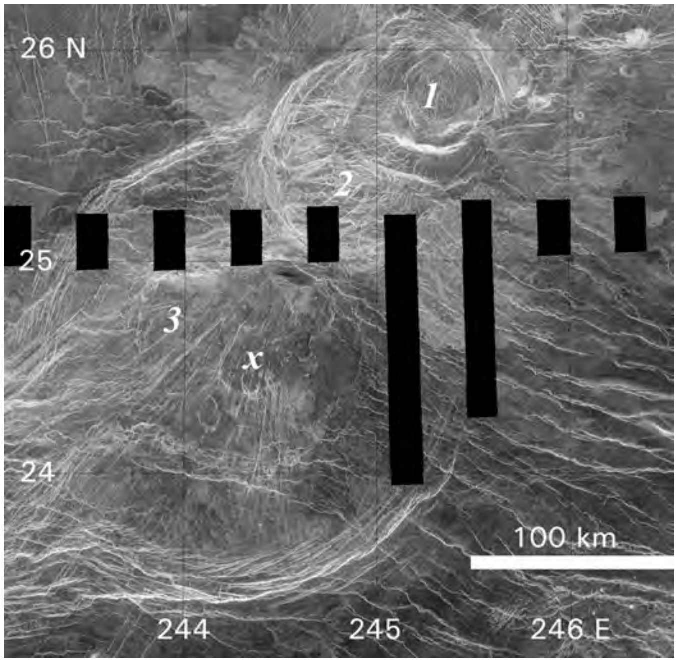

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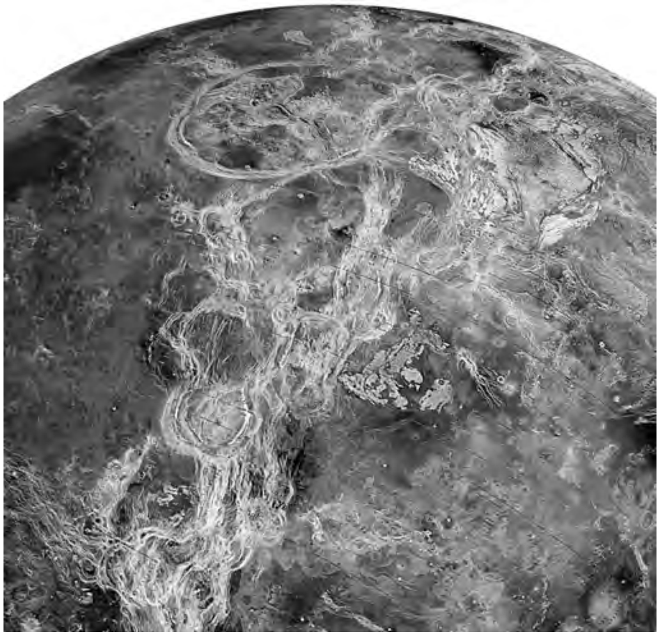

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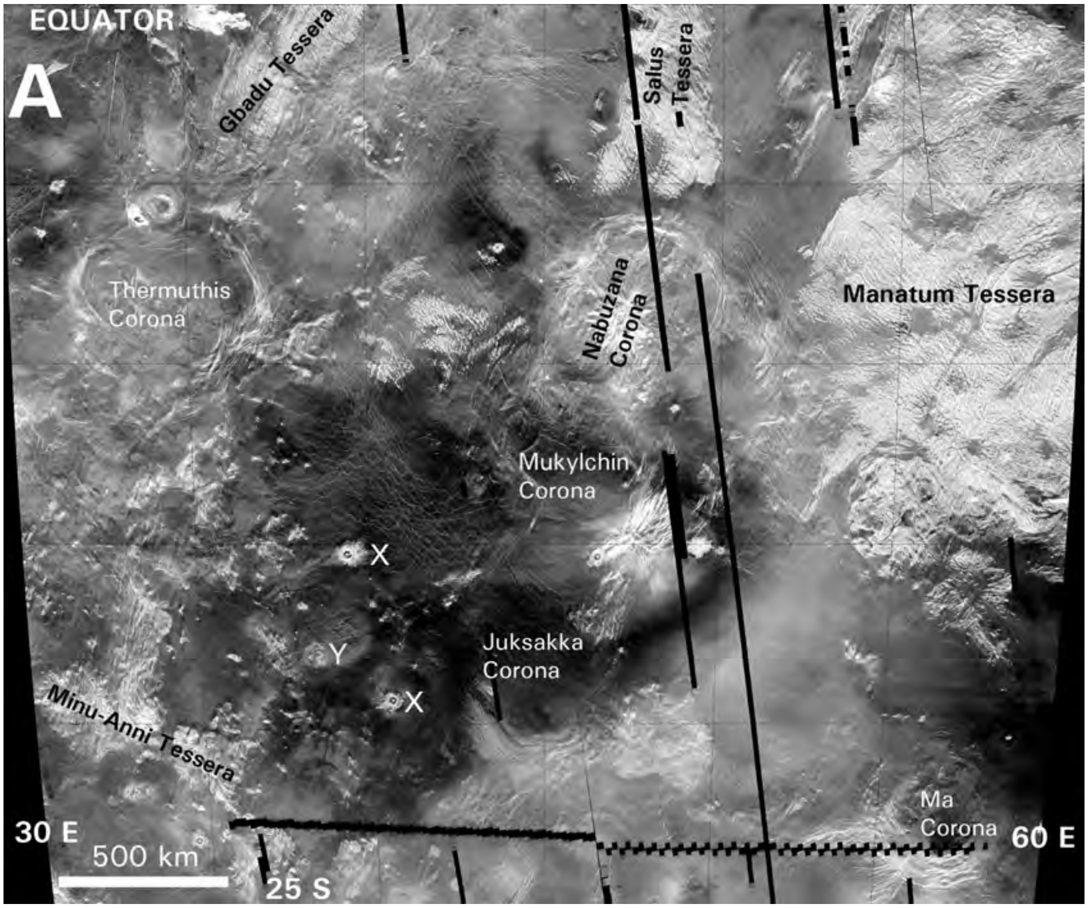

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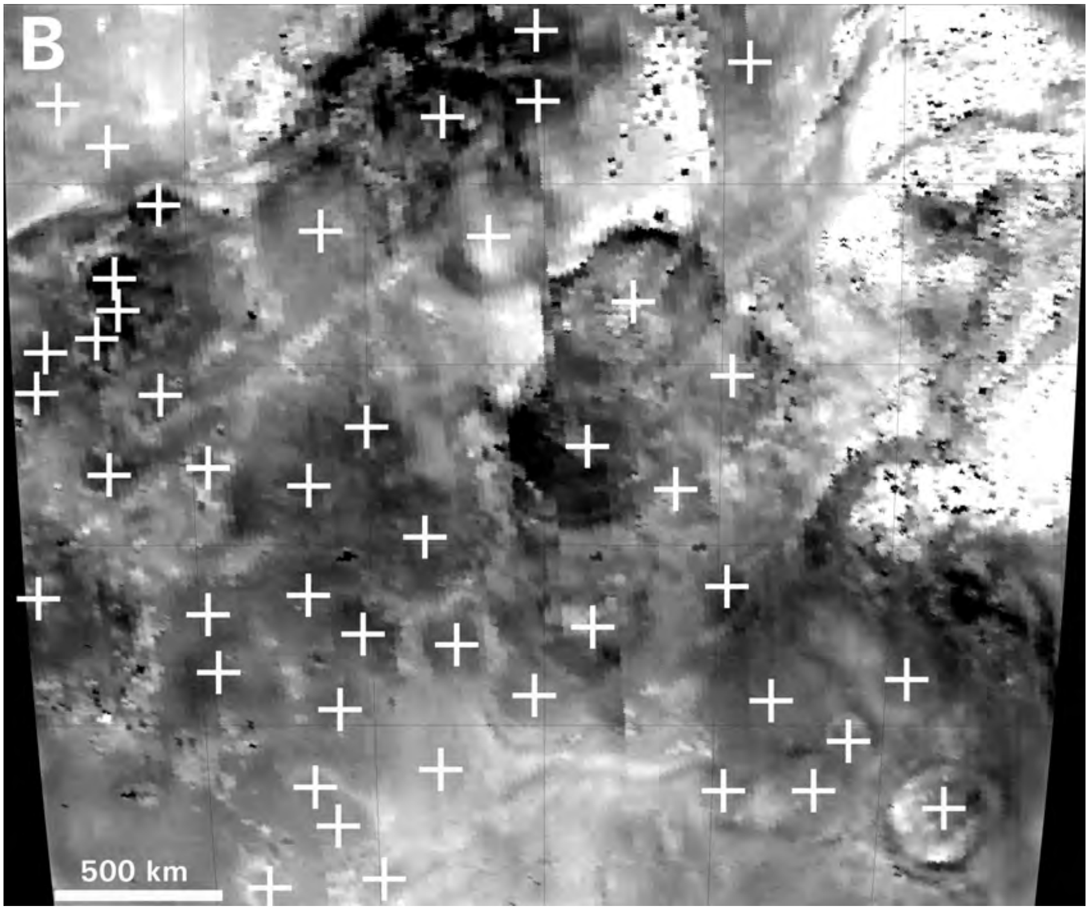

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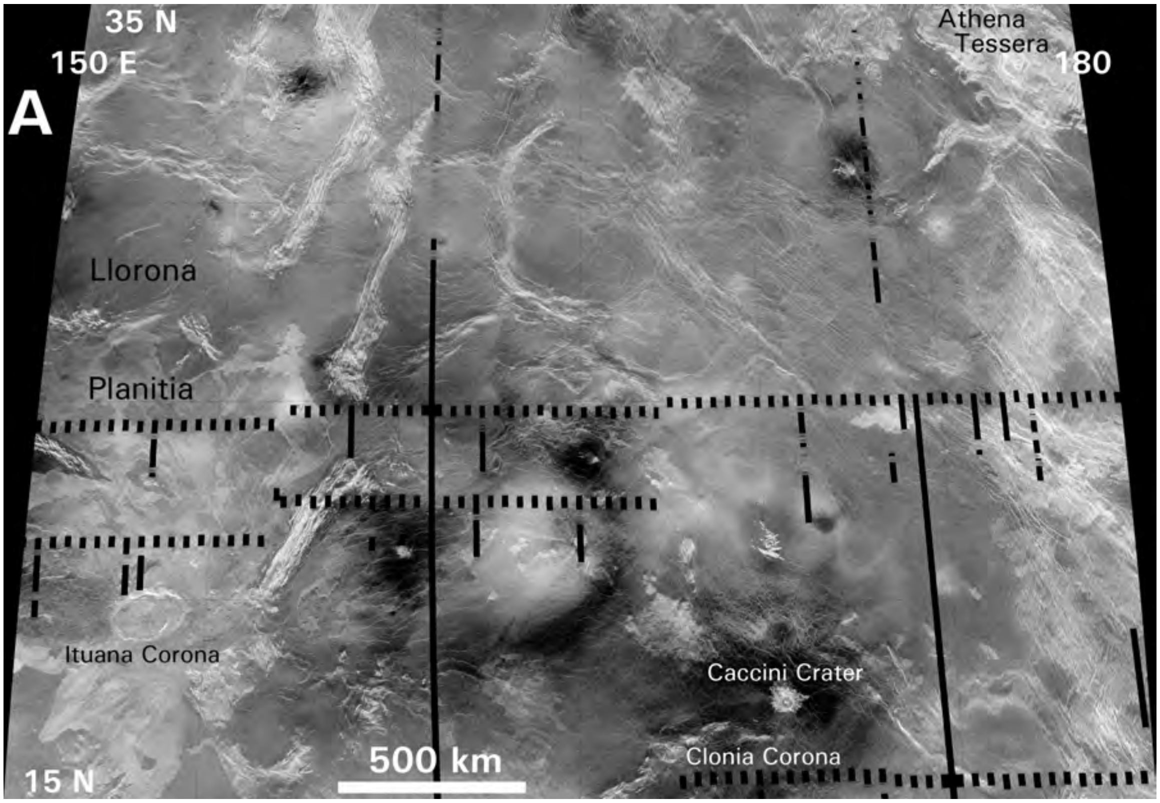
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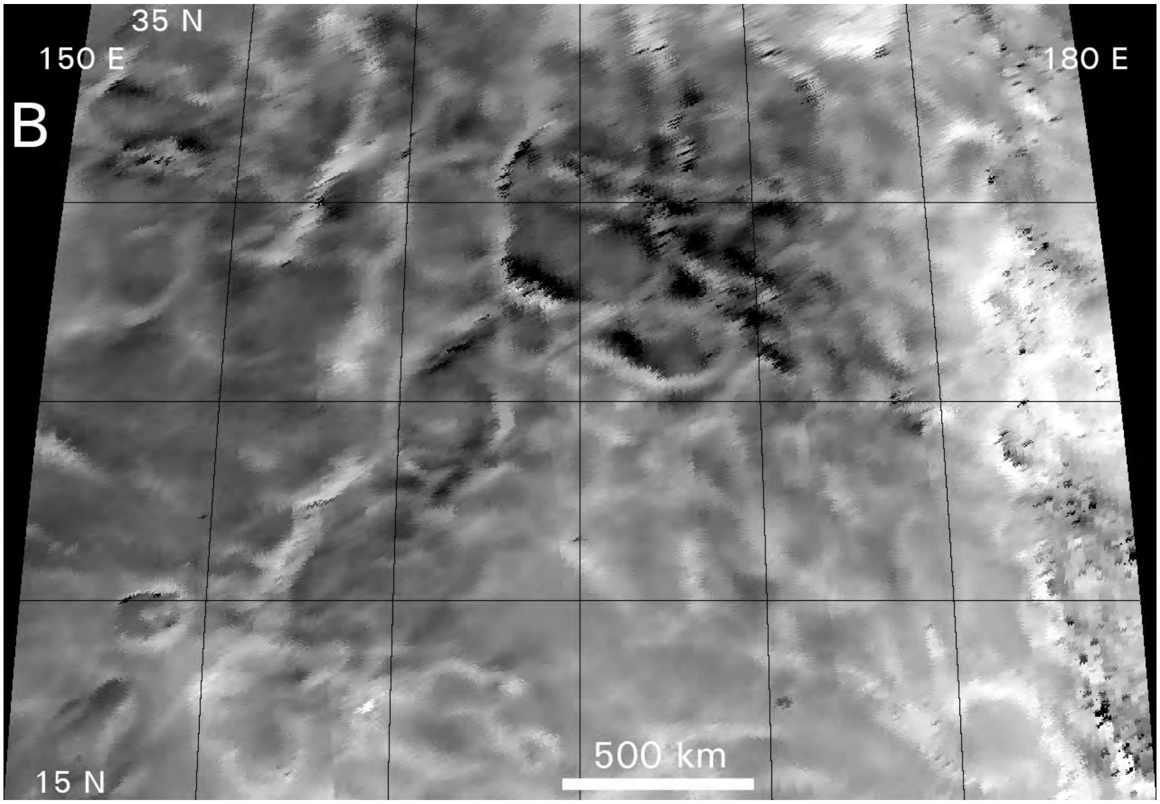
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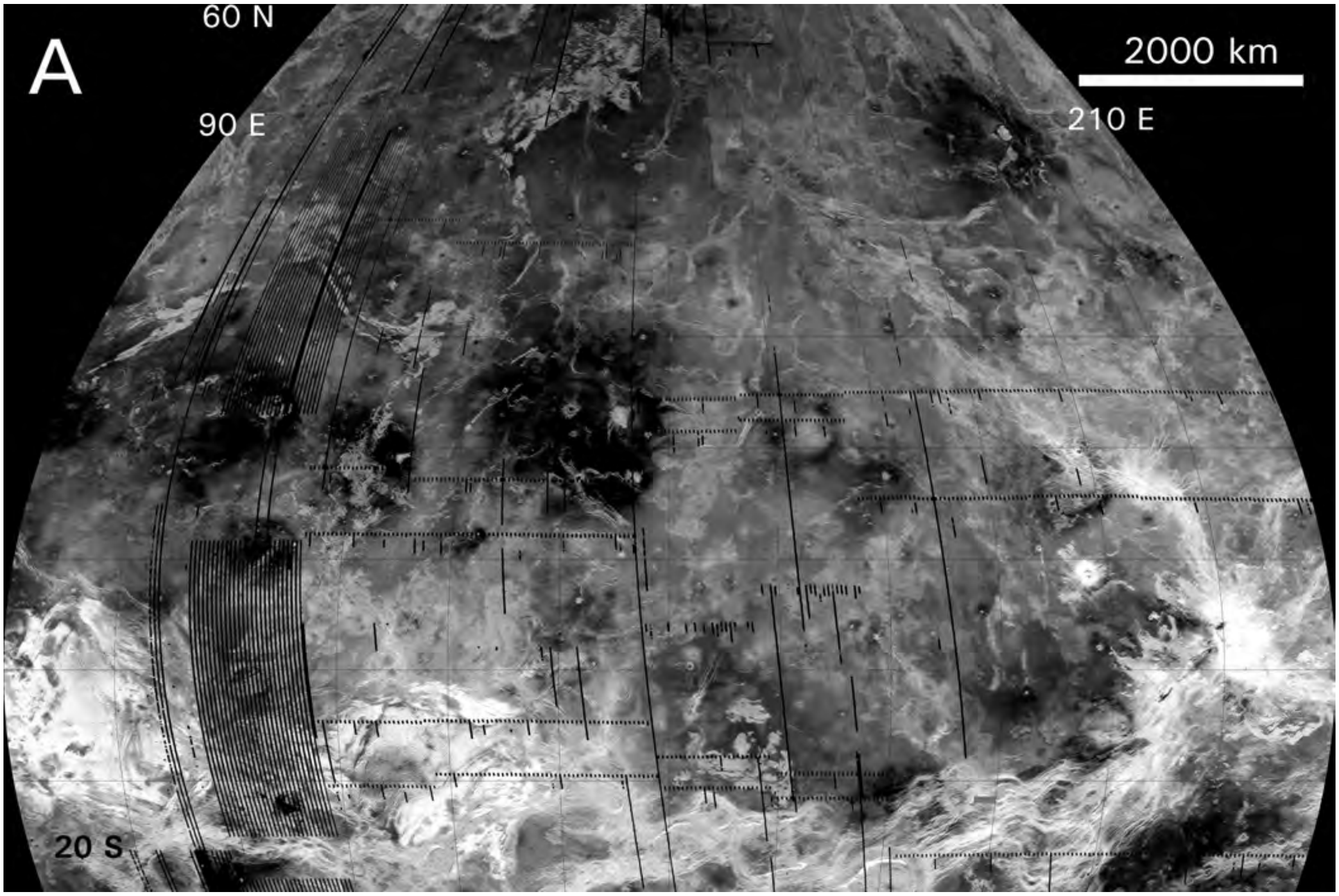

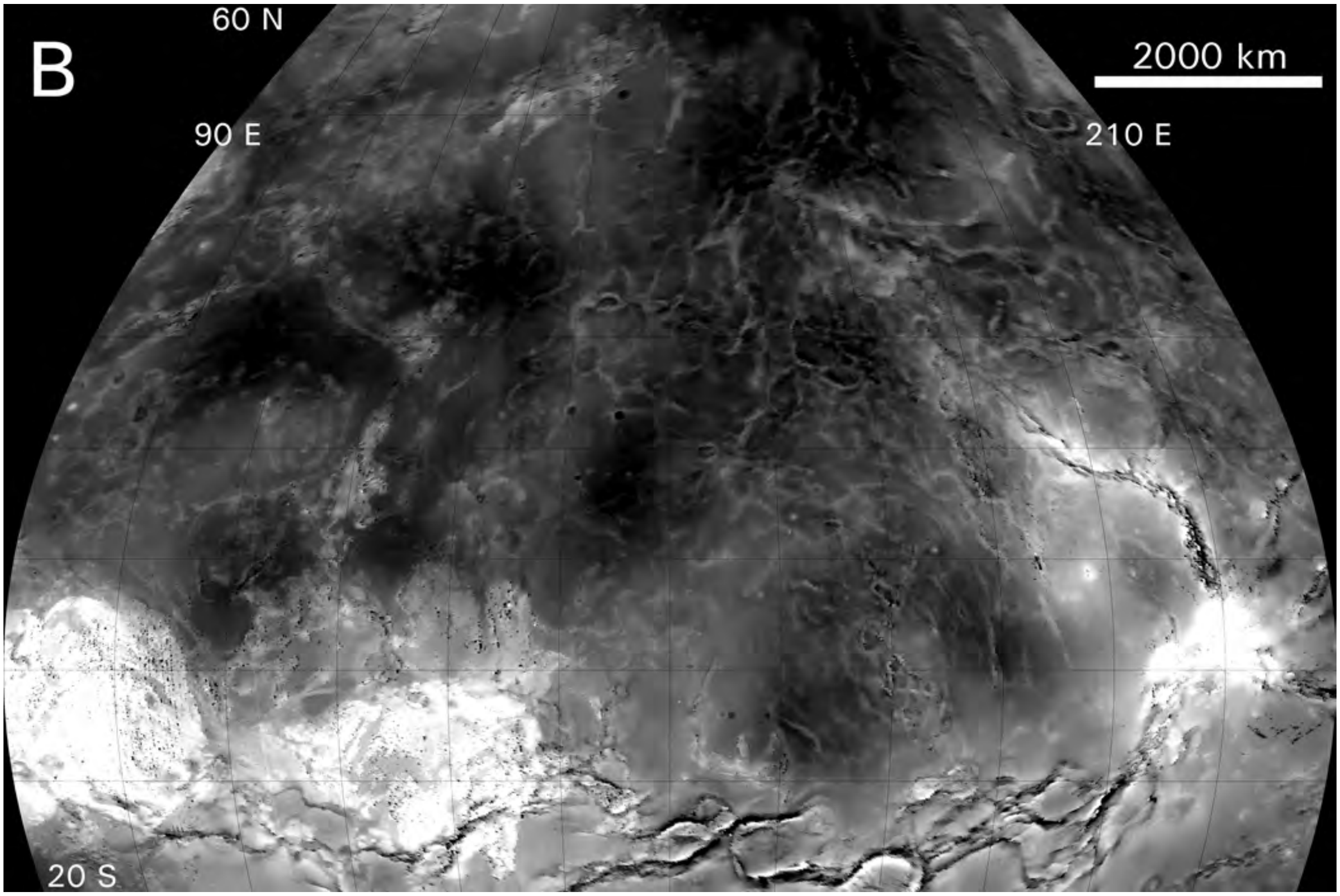

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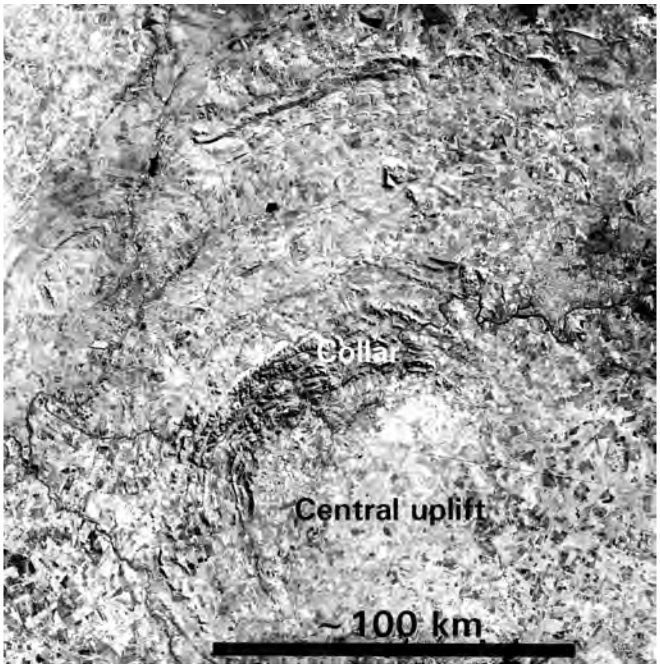

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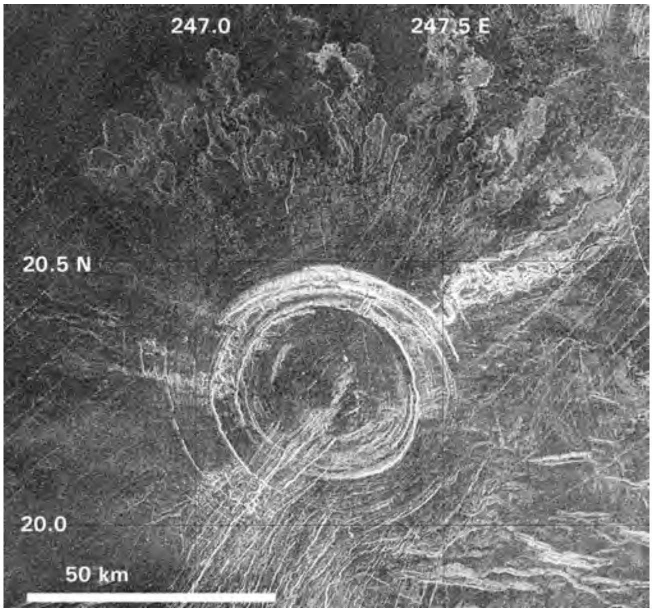

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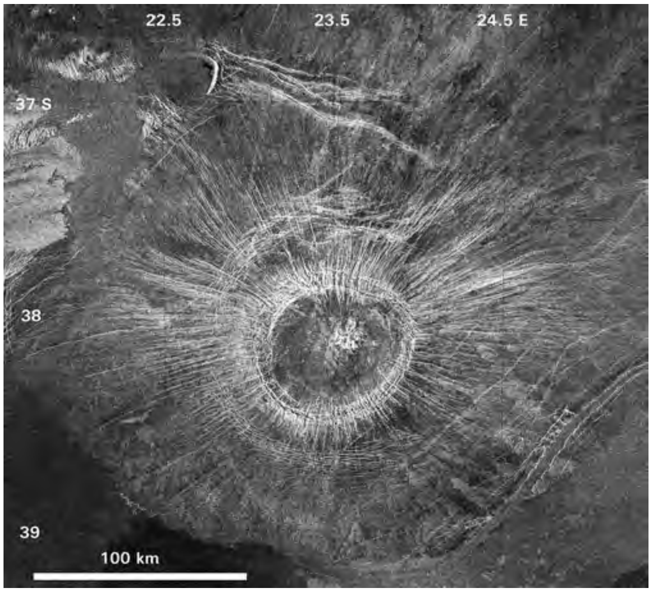

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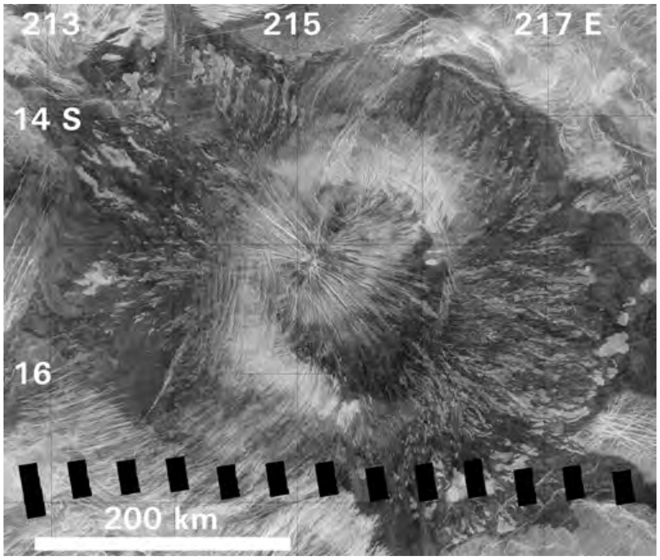

Figure 19