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Plumeless Venus preserves an ancient impact-accretionary surface

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ABSTRACT

Venus displays thousands of old circular structures, with topographic rims 5–2000 km in diameter, that have the morphology and cookie-cutter superposition required of impact craters and basins. Many structures have interior central or ring uplifts or broad, low volcanic constructs. Many are multiring. Old uplands are saturated with variably degraded structures, whereas lowland structures are variably buried by sediments. The youngest include three of the largest (rim diameters of 800–2000 km), for which analogy with the dated Imbrium impact basin on the Moon indicates likely ages of ca. 3.90 Ga. Venus is argued here to preserve much of its surface of late-stage main planetary accretion.

The Venus of conventional interpretation, by contrast, was wholly resurfaced, mostly by plume-driven processes, no earlier than 1 Ga, and preserves no ancient features. This speculation is extrapolated from terrestrial conjectures, and rationalizes away voluminous contrary evidence from Venus itself. Interpreters of early Venusian radar imagery accepted the possible impact origin and great age of the structures, but impact explanations were soon replaced, almost without analysis, by plume conjectures. Nearly all specialists now assume that Venus has internal mobility comparable to the exaggerated mobility assumed for Earth, and that the only Venusian impact structures are "pristine" small- to mid-size craters and basins with an age younger than 1.0 Ga. (Ages to 3.9 Ga for these are advocated here.) The older circular structures are conventionally attributed to mantle plumes and upwellings that deformed crust and upper mantle from beneath, with or without lava extrusion.

The "pristine" craters can be discriminated only arbitrarily from the best-preserved of the ancient circular structures. From the latter, there are all gradations back to the most heavily modified structures of the old family. Broad, low volcanic constructs (unlike any surviving terrestrial volcanoes) inside old impact basins are likely products of impact melts.

Transfer of plume conjecture to Venus from Earth has little merit. Terrestrial plume speculation is based on assumptions whose predictions have been consistently falsified. Not only do plumes probably not exist on Earth, but even the least-constrained attributions of geological and tectonic features to them do not include circular structures that in any way resemble those of Venus. Conversely, Venusian speculations neither address nor account for circularity and superpositions. The hot-mobile-Venus assumption behind young-surface conjectures is also dubious. Venus' lack of a magnetic field (its core is likely solid), its positive correlation of topography and geoid (outer Venus is far stiffer than Earth), its origin close to the Sun (less volatiles, including potassium,

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so much less early radiogenic heat, less weakening volatiles, and higher solidus temperature), and other factors indicate Venus to be much less mobile than Earth.

Venusian lowlands are floored not by young lava plains but by ancient sediments, possibly including deposits in a transient ocean, derived from uplands by processes still poorly defined. The plains are speckled with mud volcanoes (not lava cones) that, like minor deformations of the sediments, are due to top-down heating by the evolving atmosphere.

Keywords: Venus, impacts, plumes, planetary accretion geodynamics

INTRODUCTION

Much of the surface of Venus is saturated by ancient circular structures (Figs. 1, 2, and succeeding illustrations) that appear to be impact craters and basins, for which lunar analogy indicates ages older than 3.85 Ga. Venus preserves surfaces dating from late-stage main planetary accretion and, by comparison to Earth, is internally dead.

Investigators of early radar imagery saw these structures as likely or possible products of impacts. Soon, however, most investigators assumed that composition, thermal structure, and heat loss of Venus must be so like those assumed for Earth that Venus must be magmatically and tectonically too active to preserve any ancient surface. Furthermore, biased interpretation of ages of little-modified small pristine impact craters clearly younger than the old circles was accepted as precluding preservation of anything older than 1 Ga. Plumology was then exported to Venus to explain the old circular structures as endogenic, and is now overwhelmingly embraced by specialists.

The old structures have the morphology, circularity, and cookie-cutter superpositions expected of impact craters and basins. No plume models account for these features. Hundreds of the old structures retain rims and ejecta aprons, whereas others are more eroded, or are buried. The resurfacing of the ancient accretionary landscape, prior to formation of pristine impact craters, was due to erosion of uplands and burial of lowlands by sediments.

This essay is intended for nonspecialists as well as for Venusian specialists. It follows an evaluation of terrestrial dynamics (Hamilton, 2002, 2003a) that similarly rejects assumptions on which popular notions of Earth's evolution are based and reaches interpretations at odds with those widely accepted. Most geodynamic speculations incorporate the dubious assumptions—prerequisites for plumes, deep subduction, and whole-mantle convection—that Earth accreted cold, heated slowly, and is still largely unfractionated. All popular models of bottom-heated convective drives (e.g., Schubert et al., 2001) not only stem from these misconceptions but are invalidated by their inability to explain such features of plate tectonics as rollback of trenches (slabs sink more steeply than they dip), lack of crumpling of fronts of overriding plates (which thus move in response to rollback), rapid spreading of the subduction-margined Pacific and slow spreading of the passive-margined Atlantic, and trench-trench and trench-ridge collisions. I deduced a new model wherein subduction, driven by cooling from the top rather than heating from below, drives plates and plate-tectonic circulation is closed above the 650-km discontinuity.

Radar Imagery

The surface of cloud-shrouded Venus is best defined by synthetic-aperture radar imagery obtained by the Magellan spacecraft of the National Aeronautics and Space Administration (NASA) in three cycles of near-polar markedly-elliptical orbit in the years 1990–1993. Cycle 1 looked east; Cycles 2 and 3 filled some gaps in Cycle 1 and partly looked at other angles, either east or west, but have poor coverage; all three recorded radar altimetry. A fourth cycle in a more circular orbit yielded gravity data by Doppler tracking from Earth. Imagery characteristics were discussed by Ford et al. (1993), Tanaka (1994), Connors (1995), and Ward et al. (1995). The satellite was destroyed in 1994 to free funds for manned Earth-orbiting flight, but lower-resolution 1970s–1980s radar data from Earth and spacecraft fill most gaps.

Magellan data can be viewed practically only as mosaics, made mostly from Cycle 1 data (the most complete). Slant-range data are projected on a map of a low-resolution topographic surface, and features are displaced from planimetric positions where that surface differs from local topography. Mosaics are available as 1997–1998 U.S. Geological Survey (USGS) small-scale maps of the entire planet (Miscellaneous Investigations Series I-2444, nominal scale 1:50,000,000), and of the planet in eight sectors (I-2457, I-2466, I-2467, I-2475, I-2476, I-2477, I-2490, and I-2593, nominal scale 1:10,000,000). Each packet contains maps of radar brightness, radar brightness plus shaded relief, radar brightness plus colored altimetry, and layer-colored topography. The methodology was described by Batson et al. (1994). My statements regarding altitudes are taken mostly from these maps. More detailed Magellan mosaics can be studied as prints or computer displays. Easiest to access are the USGS regional V-maps on low-distortion projections but relatively low resolution (http://planetarynames.wr.usgs.gov/images, then vgrid.gif for index map, then v*_comp.pdf files for individual sheets). Seamless mosaics of any specified area can be down-

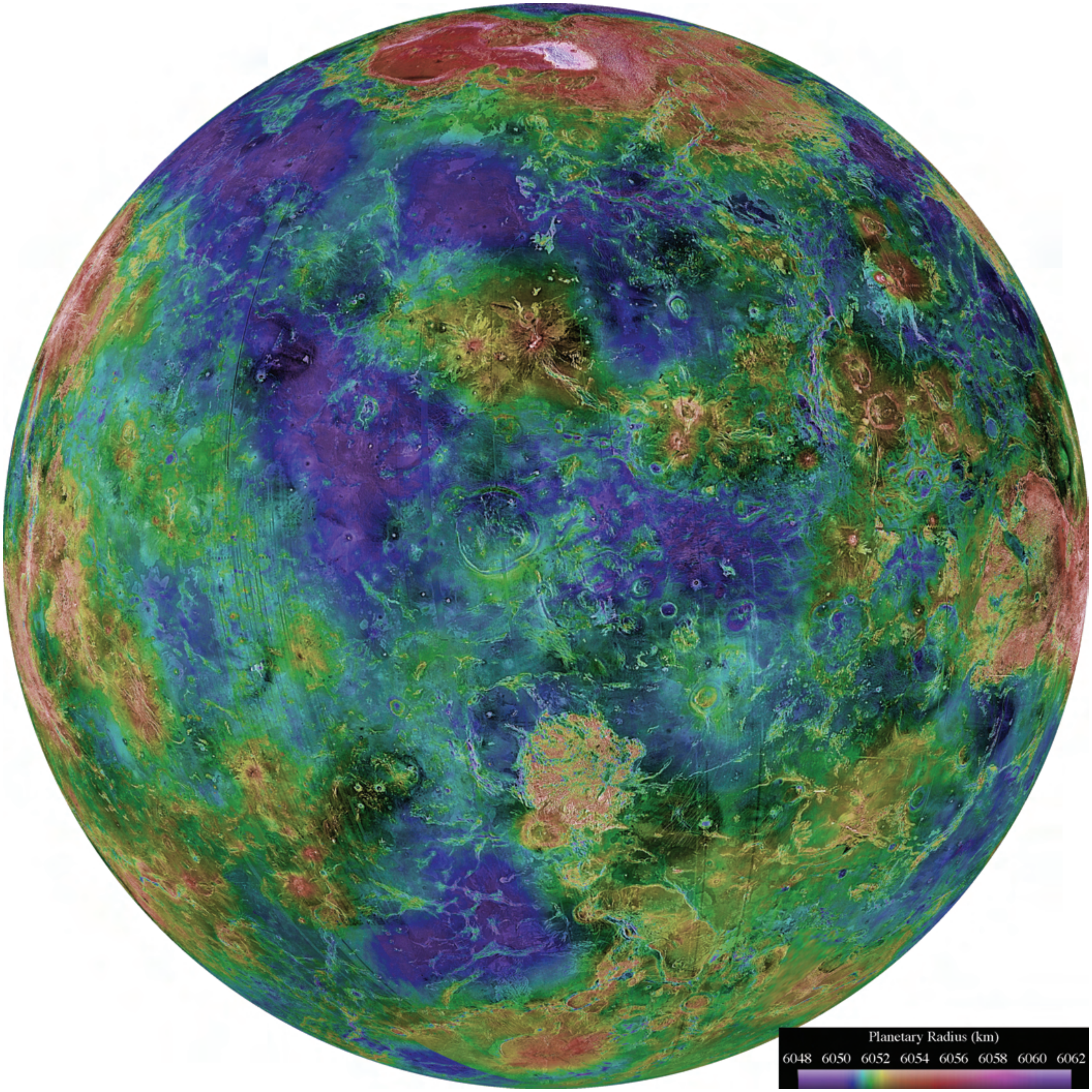

Figure 1. Hemispheric view of Venus, centered on equator (horizontal) and longitude 0° (vertical). Color indicates altitude, and shading shows radar reflectivity. Almost all circular structures visible at this scale are attributed to plumes and other endogenic processes in conventional interpretations, but are here attributed to ancient impacts. Venus is 12,100 km in diameter. Image by U.S. Geological Survey.

loaded from http://astrogeology.usgs.gov/Projects/Map-a-Planet. NASA distributes awkward-to-use CD-ROMs of small mosaics, much distorted at high latitude, at three scales and resolutions. I obtained copies of many small prints of these mosaics from NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, in 1992, and of excellent large full-resolution mosaics (F-MAPs) from the USGS in Flagstaff in 2004. I worked also with downloaded USGS images. Images in this paper are from Magellan and, unless otherwise specified, are oriented with north to the top; bar scales are generalized, as scales vary around the projections.

Radar imagery misleads those who try to read it like the vertical aerial photography it superficially resembles. Horizontal distances on photographs are proportional to optical angles,

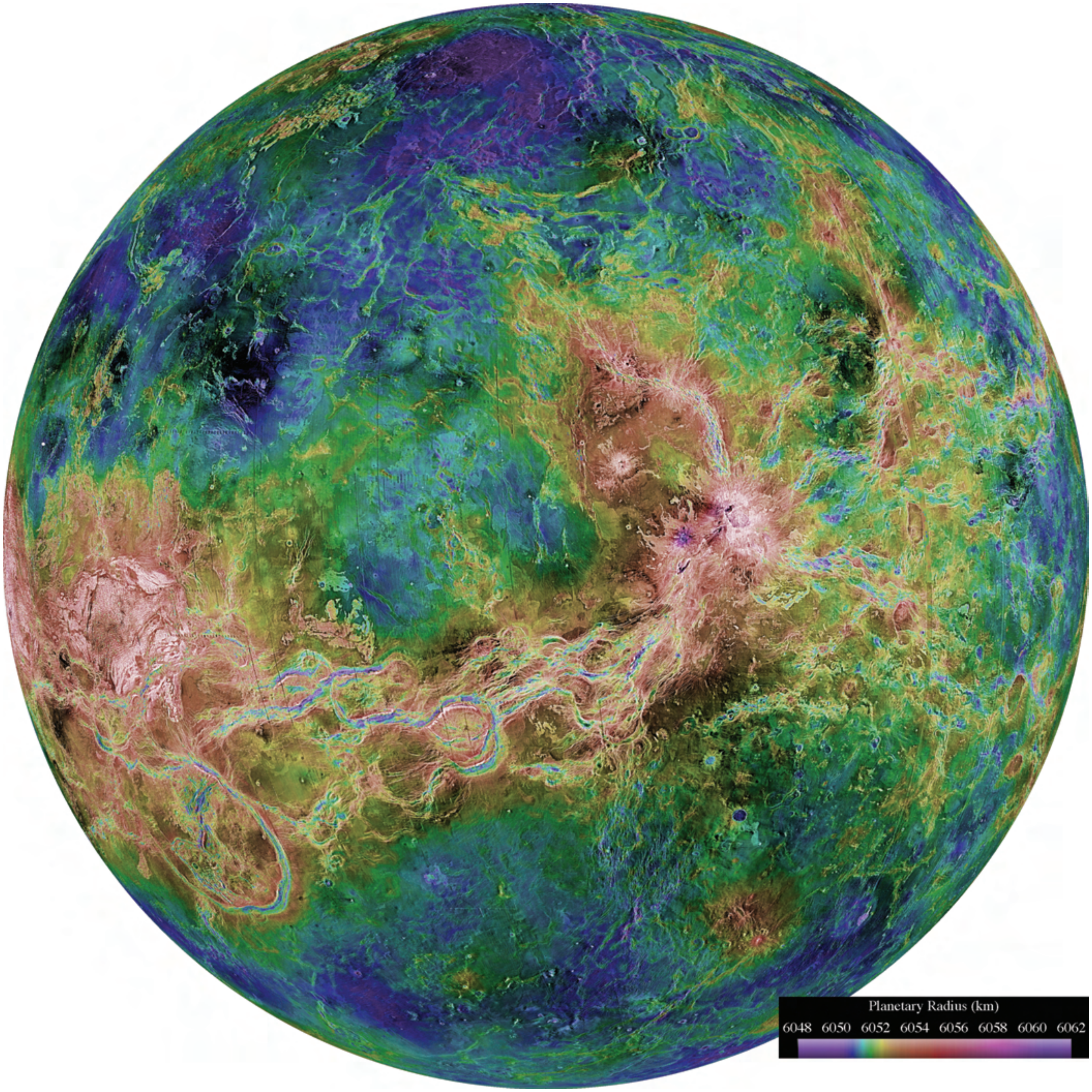

Figure 2. Hemispheric view of Venus, centered on equator (horizontal) and longitude 180° E (vertical).

so slopes facing the camera are widened, whereas slopes facing away are narrowed. Radar imagery shows the opposite effect because the horizontal scale, plotted in the look direction, is proportional to slant-reflection time. Slopes facing the satellite are shortened, slopes away are lengthened, and symmetrical ridges mimic hogbacks inclined away from the satellite. Where source-facing slopes are steeper than the complement of the incidence angle (which is measured from the nadir, not the horizontal), the tops of slopes are displayed as closer to the flight axis than the bottoms of slopes (the layover illusion). Ground features with some orientations are emphasized, and similar features with other orientations may be obscure. Incidence angles vary with cycle and latitude. Renditions of the same features by different cycles, or of similar features at different latitudes, can appear confusingly different. Furthermore, pre-Magellan images produced by earthbound and orbiting radars with different characteristics emphasize still different features.

Radar brightness records reflectivity determined by the scale, relative to radar wavelength, of surface roughness, by dielectric properties (e.g., electrical conductivity), and by the angle between the look direction and ground slope. Slopes facing the satellite are bright, whereas slopes away are dark. High-altitude surfaces are radar-bright, presumably because of dielectric properties consequent on alteration by, or precipitates from, the atmosphere. Dry, solid rock, with little covering by loose or porous materials, is generally indicated (de Pater and Lissauer, 2001, p. 183).

Matched images with opposite look directions cannot be used for optical stereoscopic viewing because of the incompatibilities between optical and radar geometry and brightness, but pairs with the same eastward look direction and different incidence angles are available for parts of Venus and can be viewed in optical stereo. The stereo images retain the layover and hogback illusions. The apparent altitudes of valleys and ridges vary as strikes and dips of slopes of the surfaces that intersect to define them change, and it is unclear to me how much distortion this adds to visual images.

Topography

Venus has unimodal topography. The very minor rifting that has occurred does not define Earthlike plates (Connors and Suppe, 2001), and plate tectonics obviously does not operate. Venus rotates very slowly in the retrograde sense and has almost no equatorial bulge. Surface altitudes are derived mostly from Magellan altimetry, which has a footprint of more than 10 km. Altitudes are expressed in terms of radius from the planetary center, or as values relative to mean planetary radius, now accepted as 6051.4 km. Slopes mostly are very gentle but can reach 60°. About 80% of the surface is within an altitude range of 2 km, although extreme altitudes range from –3 to +11 km (Rosenblatt et al., 1994).

Many reports contain pseudoperspective images, mostly made by draping radar-brightness mosaics on digital-altimetry models. These are informative only when their distortion is understood, for all published images have extreme vertical exaggerations, from 10:1 to 50:1, which grotesquely misrepresent actual relationships and yet commonly are not mentioned in captions. Slopes of a few degrees are depicted as gigantic mountains. Few readers will recognize impact structures with these distortions. As the altimetry models are based on large-footprint data, the great exaggerations also produce lumpy artifacts. Two pseudoperspective images, with exaggerations of only 3:1, accompany this paper (see Figs. 4 and 14 below).

Important but gentle topographic features can be difficult to see in the radar-brightness imagery. By seeking circular ridges primarily in the altimetry, Tapper et al. (1998) found ~200 previously unrecognized large rimmed structures, primarily in lowlands, of the type here attributed to ancient impacts.

Terminology

Venusian literature is fogged by terminology that impedes comprehension by nonspecialists. The following several terms are used for physiographic features of particular interest here, and their conventional definitions are followed by my annotations in brackets. For a searchable database of Venusian geographic names, incorporating these and other terms, see http://planetarynames.wr.usgs.gov.

Impact craters. Approximately one thousand unambiguous impact structures, maximum rim diameter 270 km, with sharp topography and obvious ejecta aprons. [Never applied in the standard literature to the older structures here assigned impact origins.]

Corona/coronae. Approximately seven hundred circular and near-circular volcanotectonic features, many of them both rimmed and multiring, with strong concentric structure, mostly 100–500 km in inner-rim diameter but reaching 2000 km. [Ancient impact structures.]

Nova/novae. Radially fractured centers, commonly broad, low domes, 100–300 km in diameter but only 1 km or so high, mostly centered within large coronae, and attributed to mantle upwellings. [Central uplifts and impact-melt constructs in impact structures.]

Arachnoid. Structure with both concentric and radial structures. [An ancient impact structure. Hundreds more old circular impact structures that do not fit these pigeonholes, and perhaps thousands of small ones, mostly go unmentioned in published descriptions.]

Planitia, or *Volcanic plain*. Lowland low-relief lava surface. [Nonvolcanic sediments.]

Shield field. Cluster of small, low volcanic cones rising from a plain. [Mud volcanoes.]

Terra, a huge upland region; *regio*, regional highland; *mons*, mountain. [Usually very broad and low.]

Impacts produce deep transient craters, and all but the smallest craters promptly rebound. Beyond erratic threshold sizes, their walls migrate outward by slumping toward the transient crater and melt masses. The term *basin* is commonly applied to structures whose final rims are far outside transient craters, but the distinction between *crater* and *basin* is arbitrary and I imply no consistency in my usage.

COMPOSITION, TEMPERATURE, AND PROPERTIES

The major conclusion of this essay—Venus preserves an accretionary surface older than 3.9 Ga—can be correct only if widely accepted assumptions about the properties and thermal history of the planet are mistaken. Venus is commonly assumed to have a composition and behavior like that dubiously presumed for Earth: Venusian mantle is either unfractionated or compositionally inverted; little crust has yet separated from it; and Venus is internally active, even though its surface is inactive. Diverse datasets indicate otherwise. Furthermore, mainline explanations of Venus assume the maximum age of little-modified impact craters to be younger than 1 Ga, which in turn requires that the planet be wholly resurfaced by magmatism and tectonism in this period, most activity having occurred early. Venus lacks Earth-like plate tectonics, so unearthly mechanisms are speculated to account for the postulated resurfacing.

All mainline interpretations of observed geologic features are fit to these assumptions, which most specialists in Venus misstate such assumptions as facts. Only a few authors recognize the assumptions as unproved. Among them, Schubert et al. (2001) specified that they assume Venus to have the same radiogenic heating and high mantle temperature as does Earth. Brown and Grimm (1999) based their modeling on the assumption that Venus has the same per-volume heat loss as Earth, and accepted speculation that Earth's heat loss is 44 TW—a value speculatively increased almost 50% above that indicated by measurements, as discussed subsequently—and that internal mobility is controlled entirely by heat.

Strong, Stiff Venus

Various datasets indicate Venus to be much stronger and less mobile than Earth. These data are rationalized away in popular models.

Solid Core. Venus lacks a magnetic field, so it is an obvious inference that the core is solid (Lewis, 1997; Head, 1999). As even the liquidus temperature of (Fe, Ni, S) at appropriate pressure is below the solidus of (Mg > Fe) perovskite—the likely dominant lower mantle silicate—the lower mantle would be so cool that its viscosity would be extremely high, and plumes unlikely (cf. Zerr and Boehler, 1994; however, heliocentric zonation of sulfur might have resulted in a core with a higher solidus temperature than Earth's). Rapidly rotating Earth is strained at high rates by lunar tides, and to a lesser extent by solar tides, which have decreased with time as the distance between Earth and Moon has increased and rotation has slowed. Amount and partitioning of heat in the Earth is disputed, but perhaps tidal heating of the core contributes to maintaining the terrestrial dynamo.

Gravity, Topography, and Strength. All variants of the standard model for Venus are made implausible by the relationship between gravity and topography. Venusian gravity, determined by satellite tracking, is commonly displayed as spherical harmonic expansions of the geoid or of gravitational-potential anomalies. Positive correlation of the Venusian geoid with topographic features having dimensions on the order of 400–6000 km (Simons et al., 1994; Johnson and Richards, 2003) shows Venus to be strikingly unlike Earth. Venusian highlands are geoid highs and lowlands are lows, with strong correlation of shapes and moderate correlation of amplitudes. On Earth, regional topography is compensated isostatically, mostly at shallow depths, and is all but invisible in the geoid. Large terrestrial geoid highs and lows are almost randomly arrayed with regard to land, sea, and topography, and the most obvious fit to shallow features is that some regional highs correlate broadly with regions within which subduction is active, and some lows correlate broadly with regions that have not had subduction for more than 200 m.y. The same contrast between the two planets is shown by the positive correlation of topography and gravitational potential. On Venus, the correlation continues to strengthen for harmonic degrees from 40 to 3, whereas on Earth, the correlation weakens (Sjogren et al., 1997).

These striking contrasts require near-surface Venus to be stronger and stiffer than Earth and depths of isostatic compensation to be generally much deeper (Kaula, 1994; Simons et al., 1994; Kucinskas et al., 1996; Solomatov and Moresi, 1996). This difference is readily explained if Venus is much colder (or dryer) internally than Earth, despite the high surface temperature to which its shallow geotherm is graded. Venus lacks both an asthenosphere—its upper mantle nowhere approaches solidus temperature—and the ductile lower crust of many terrestrial continental regions.

Bad Assumptions Transferred from Earth

The popular notion that Venus must be internally highly mobile is derived by extrapolation of terrestrial assumptions, not from Venusian data. Terrestrial geodynamics and geochemistry are shackled to bad assumptions made in the 1950s and 1960s. Meteorites were then wrongly assumed to represent the composition of terrestrial planets, and isotopic and trace element studies were in their infancy. Urey (1951) and others speculated that Earth accreted cold and heated slowly by radioactivity and by still-incomplete gravitational separation of the core. By the mid-1960s, the core was known to be now more or less completely separated, but part of the old speculation had become (and remains) geochemical dogma: Earth's lower mantle is still largely unfractionated, whereas the upper mantle is highly depleted by extraction of crust.

We know now that Earth fractionated very early—and yet much conventional geochemistry and geodynamics retains the crippling assumption that the mantle is inverted compositionally. Concepts of whole-mantle convection, and of plumes rising from, and slabs subducting to, deep mantle, depend on this inverted-mantle assumption and are incompatible with constraints from mineral physics (e.g., very low thermal expansivity at lower-mantle pressure, and very high viscosity of much of the lower mantle because it is far below its solidus temperature: Zerr and Boehler, 1994). The inverted-mantle concept is further discredited because geodynamic models incorporating it, although popular, account for almost no characteristics of actual tectonic plate motions and interactions. I discussed these problems at length (Hamilton, 2002, 2003a) in deriving alternative explanations for Earth's evolution and behavior.

The bad assumptions of terrestrial geochemistry and geodynamics have been transferred en masse to Venus. They fit it poorly and have been embroidered with secondary and tertiary speculations.

Accretion and Fractionation

Venus likely had accreted to almost its final size and was fractionated into core, crust, and mantle by 4.45 Ga or soon thereafter. Early shallow concentration of incompatible and volatile radioactive elements is probable.

Condensation of solid material in the inner solar system began ca. 4.56 Ga, and planets reached almost their present sizes, and were fractionated, before 4.4 Ga. Accretion simulations show that Venus and Earth received most of their present material within ca. 100 m.y. of the beginning of condensation. The oldest dated crustal materials of Earth and Moon are ca. 4.40 and 4.45 Ga, respectively. Tungsten isotopes indicate separation of Earth's core before 4.45 Ga (e.g., Mezger et al., 2004). Systematics of short-halflife ^{146}Sm-^{142}Nd are interpreted by Caro et al. (2004) to require the separation of Earth's crust and mantle by ca. 4.46 Ga. Similar methodologies applied to Martian meteorites indicate major fractionation of core, mantle, and crust by ca. 4.45 Ga (Harper et al., 1995; Hess, 2002). Dating of lunar samples shows that large bolides continued to accrete until ca. 3.90 Ga but added only a very small proportion of additional mass after 4.45 Ga. Many planetoids from which came fractionated inner-asteroid meteorites were differentiated by 4.50 Ga (e.g., Srinivasan et al., 2004), and nearly all before 4.0 Ga.

Early fractionation of planets presumably was a response to their rapid accumulation of impact (and contained?) heat from bolides, augmented by short-lived radioisotopes. Formation of Earth's Moon is plausibly attributed to an Earth-melting late-accretion impact by a planet larger than Mars. Perhaps Venus missed such an event, but the unpredictability of accretion scenarios precludes quantitative analysis.

Heliocentric Zoning of the Inner Solar System

The moderately volatile elements that lower the melting temperatures of rocks and enhance mobility must be markedly less abundant in Venus than in Earth.

The asteroids and inner planets accreted from solar disk materials whose minimum temperatures of major condensation increased sunward from Jupiter. (Tiny iron-rich, eccentric-orbit Mercury likely is a fragment, perhaps captured, of a larger planet.) The terrestrial planets formed by runaway violent and hot accretion of progressively larger bolides, with only minor material likely added to Earth and Venus from farther out than the inner part of the asteroid belt (Wetherill, 1994; Chambers and Wetherill, 2001; Chambers and Cassen, 2002). Asteroids show heliocentric compositional zonation, with overlaps and irregularities such as are expected from orbital perturbations (Bell et al., 1989; Mothé-Diniz et al., 2003). Asteroids of the outer half of the belt are dominated by ices and organic compounds and have no meteoritic analogs. Asteroids next sunward are dominated by silicates, hydrous silicates, and organic compounds and provide the fragile and uncommon carbonaceous-chondrite meteorites once thought to be major building blocks of terrestrial planets. Inner asteroids consist mostly of silicates and metal, largely lack H, C, and N, and produce most meteorites.

Thermal fractionation continued sunward through the main feeding zones of the terrestrial planets. Ratios of major and trace elements and isotopes in terrestrial rocks require that Earth accreted mostly from sources more depleted in elements and compounds of moderate and low condensation temperatures than are meteorites from even the inner part of the asteroid belt (O'Neill and Palme, 1998; Allègre et al., 2001; McDonough, 2001; Taylor, 2001). Modern geochemists who deduce bulk-Earth compositions nevertheless assume that the lower mantle preserves its accretionary composition and is little fractionated, except for separation of the core. The 1950s rationale of a mantle inverted in composition is perpetuated by uncritical geochemical normalization to, and calculations from, "bulk silicate Earth," "primitive mantle," or "undifferentiated mantle." Anderson (2002) and Hamilton (2002, 2003a) summarized evidence for irreversible fractionation of the mantle into a lower refractory part isolated from an upper active mantle-plus-crust part.

Venus is close to Earth's size and mass, and has a mean radius of 6051 km (Earth's is 6371) and a bulk density of 5.24 g/cm^3 (against 5.52; Lodders and Fegley, 1998). As Mg and Fe have high and similar temperatures of condensation (50% at ~1065 °C; Lodders and Fegley, 1998), it is probable that Venus, like Earth, has an (Fe, Ni) core and a mantle dominated by (Mg > Fe) silicate. Uranium and thorium are even more refractory and presumably have similar abundances in both planets. Much-more-volatile potassium, also important for radiogenic heat and thermal evolution, however, was ~50% condensed only after cooling to ~750 °C, and almost completely condensed only at ~675 °C (Fegley and Lewis, 1980). If temperature was greater than ~800 °C during condensation of solid particles in the main Venusian feeding zone, Venus would have received little K. The same conclusion follows from known heliocentric zoning. The K/U ratio in meteorites from the medial and inner asteroid belt varies within the range of 20,000:1 to 100,000:1, without obvious heliocentric zonation, but displays thermal fractionation sunward from the asteroids. The ratio is ~15,000:1 in Martian meteorites, and ~10,000:1 in widely varied terrestrial rocks. The K/Th ratio similarly is erratically high in asteroidal meteorites, much lower (near 3800:1) in Martian surface rocks as integrated by orbiting gamma-ray spectrometer (Taylor et al., 2003), and still lower (~2700:1) in terrestrial rocks. Apparently K decreases sunward from the asteroids through Mars to Earth and, by extrapolation, on to Venus. K, U, and Th are incompatible in most silicate structures and likely all are concentrated in the outer part of the Earth and depleted in the deep interior (Hofmeister and Criss, this volume). Venus should be similar.

The absence, or scarcity, of felsic Venusian crustal rocks is another indicator of low planetary content of materials of low condensation temperature. Basaltic rocks apparently characterize the surface. Dielectric properties and radio and radar scattering are compatible with basaltic composition (Pettengill et al., 1997). Three Russian landers on Venusian plains made semiquantitative partial chemical analyses by X-ray fluorescence (Lodders and Fegley, 1998) and defined broadly basaltic compositions, with 0.1, 0.2, and 4.0 wt% K_2O (error estimates omitted). Five gamma-ray spectroscopy determinations of K, by one of the same landers and four others, indicated higher values, equivalent to 0.3, 0.5, 0.5, 0.6, and 5.0 wt% K_2O. The one lander that used both methods reported 0.1% K_2O by fluorescence, but 0.5-equivalent by spectroscopy. The cause of the bias is unknown. The median value of these erratic determinations is 0.5% K_2O equivalent—less than most terrestrial basalts other than the misleadingly designated “normal” mid-ocean-ridge basalt (N-MORB) subset of oceanic basalts filtered to remove higher-K analyses.

The Venusian atmosphere, despite its density and its very high content of nonradiogenic Ar, contains only ~1/4 as much total ^{40}Ar (one daughter of ^{40}K) as does Earth’s atmosphere. The simplest explanation is that Venus has a much lower content of K than has Earth.

Radiogenic Heat

The likely much lower content of potassium in Venus than in Earth indicates that although the present Venusian productivity of radiogenic heat is only moderately lower than Earth’s, past productivity was vastly lower. Little radioactive ^{40}K now remains because it has a halflife of only 1.25 b.y., but it was a major contributor to early Earth’s heat. The ratio K/U/Th varies little from 10,000:1:3.7 over a wide variety of terrestrial rocks (Van Schmus, 1995). For these proportions, K produces only ~15% of present radiogenic heat, but it alone produced almost twice as much heat in the young Earth as all radioactive elements do now.

Water and CO_2

Volcanic gases are rich in H_2O and CO_2, and conventional geochemistry and geodynamics ascribe these—and by extension Earth’s—surficial water and carbon, in substantial part to outgassing from still-fractionating, primordial materials. However, materials accreting from Earth’s main feeding zone likely were exceedingly dry, and atmosphere, hydrosphere, and carbon instead came mostly from bolides originating in the zones of the medial and outer asteroids (not from long-period comets), as minor additions late in the period of main accretion (Morbidelli et al., 2000; Alexander et al., 2001). Earth’s upper mantle may now contain appreciable water and carbon primarily because subduction mixes them downward into upper mantle—and subduction likely began only ca. 2.0 Ga, and affects only the upper mantle (Hamilton, 2002, 2003a).

Water and CO_2 increase mantle mobility by both lowering melting temperatures and weakening materials. Without them, neither plate tectonics nor substantial volcanism might now operate (Anderson, 1989). Venus probably accreted with less volatile material added from either its main feeding zone or farther out in the solar system, and certainly it has had no plate tectonics within the period (probably >4 Ga) represented by its landscape. Lack of volatiles in Venusian upper mantle increases strength, inhibits mobility, and curtails magmatism, regardless of whether Venus is also cooler than Earth.

Heat Flow

Conventional Earth models—and thus Venusian models extrapolated from Earth—may be built on an overstatement of terrestrial heat loss by almost 50%. Earth’s measured surface heat loss, integrated for crustal age, is ~31 TW, and this likely is close to the true value (Hofmeister and Criss, this volume). The widely assumed larger value of ~44 TW is deduced not from measurements, but from speculations falsified by mineral physics. Measured heatflow in young oceanic crust is generally low, even though the subjacent lithosphere is thin, and very high substitute figures are calculated with the false assumption that thermal conductivity of oceanic lithosphere is that of cold rock from top to bottom, and that the enormous excess of heat thus calculated over the measurements for young lithosphere is lost to circulating seawater. In reality, the lattice-vibration component of conductivity decreases greatly with increasing temperature within the range of lithospheric temperature, and total conductivity is only ~40% as large in near-solidus basal lithosphere as near the surface. When this is taken into account, measured and calculated oceanic heat flows are similar. With this actualistic value, oceanic heatflow is comparable to continental heatflow (Hofmeister and Criss, this volume), whereas it is twice as high in conventional assumptions. The smaller value is compatible with (but not required by) the closed-upper-mantle circulation model of Hamilton (2002, 2003a), but not with popular geodynamic models.

Earth’s upper mantle has cooled ~400 °C since 4 Ga (Hamilton, 2002, 2003a), but deducing core and lower-mantle cooling from this and from heatflow is made ambiguous by many uncertainties, including the role of barriers to convection in the mantle.

Plumology

The standard model for Venus assumes that plumes of hot material rising from basal mantle produce myriad, but unearthly, tectonic and magmatic effects at the surface. This speculation is extrapolated from popular conjecture that narrow plumes of hot, fertile material rise from the base of Earth's mantle to the crust. For neither planet does such conjecture appear viable.

Plumes Do Not Exist on Earth. Plumes represent an abstract speculative concept for Earth, wholly unrelated to well-substantiated plate tectonics. Many predictions of terrestrial plume conjectures have been falsified, and all purported evidence for plumes is better interpreted without them (Anderson, 2000, this volume; Hamilton, 2002, 2003a; Anderson and Schramm, this volume; see www.mantleplumes.org for extensive discussions by others). The response by plume proponents to disproofs of predictions is to increase the complexity of models to make them untestable and unique to each example: plumes move erratically, jump, split, reverse course, turn on and off, and have variable heads, tails, offshoots, and durations that produce any desired results. Geochemical plume conjectures are similarly convoluted, circular, and impervious to evidence.

No plumes extending downward into lower mantle have been detected by unambiguous tomography (Dziewonski, this volume; Julian, this volume). Purported plume displays are flawed in coverage, methodology, artifacts, and presentation. Most purported plume-topping hotspots do not overlie abnormally hot upper mantle, most tomographically inferred hot regions are not overlain by purported hotspots, and there is no indication of plumes in upper mantle geophysics (Anderson, 2000; Anderson and Schramm, this volume). Oceanic asthenosphere is everywhere near solidus temperature, so that local excess heat is not required for island volcanism. Access of melt to surface (e.g., by propagating rifts) is needed—crackspots, not hotspots. Island alignments reflect regional stresses, perpetuation of directions once established, and properties of the lithosphere.

Venusian Plumology. Features speculated to be due to plumes on Earth are lacking on Venus, so quite different effects are conjectured for Venus. Most specialists postulate a hot and internally active Venus wherein topography is dynamically controlled by rising and sinking narrow currents—hot plumes and cold antiplumes, the latter not being part of terrestrial mythology —that push stiff lithosphere up and pull it down, and by plume-related convective flow that thickens and thins stiff lithosphere. Large uplands are attributed to dynamic uplift by continuously rising hot mantle (Bindschadler and Parmentier, 1990; Head and Crumpler, 1990; Kiefer and Hager, 1991a; Sandwell et al., 1997; Smrekar and Stofan, 1999; Schubert et al., 2001; Johnson and Richards, 2003; Stofan and Smrekar, this volume). Or the same or similar uplands are attributed to formation by compressive crustal thickening above currents converging toward sinking antiplumes (e.g., Kiefer and Hager, 1991b; Lenardic et al., 1991; Hansen and Phillips, 1995). Or the same or similar uplands are attributed to structural thickening by platelike subduction, although geometric surface-plate balancing cannot be made (e.g., Head, 1990; Suppe and Connors, 1992). Large lowlands are commonly attributed to dynamic downpulling by antiplumes; but the surfaces of the same lowlands are attributed to volcanism due to rising plumes, or to rifting (hence divergence, not convergence), or to both plumes and rifting (see review by Stofan and Smrekar, this volume).

Theorists model backward from mobile-planet assumptions, so most geophysical modeling of Venus merely illustrates those assumptions. Such manipulation carries "a danger of wish fulfillment" (Kaula, 1995, p. 1463). Thus, Barnett and McKenzie (2000, p. 1) "remove the long wavelength component of the topography which is dynamically supported by active convection in the mantle, before modelling the lithospheric flexure" from which they cantilevered further speculations. Modelers assume properties and parameters as needed to derive their preferred configurations and behaviors of crustal and mantle layers. Among the few who note that this indeed is what they are doing, Vezolainen et al. (2003, p. 1) conceded that "it is difficult to satisfy simultaneously" their assumtions, which they nevertheless adjusted until a desired solution was obtained. Misfits are casually disregarded: Kaula et al. (1992, p. 16, 118) made the non sequitur claim that the great depth of isostatic compensation required by geoid/topography ratios is "suggestive of deep mantle plumes."

The standard model requires that the configurations of Venusian lowlands and diverse highlands have changed little for hundreds of millions of years. The dynamic-topography rationale thus requires that up and down elevators indefinitely maintain their positions, sizes, shapes, and buoyancies.

Plumes Do Not Exist on Venus. Plumology came to Venus as speculation extrapolated from conjecture that Earth has plumes and was adapted to explain structures whose only planetary analogs are impact structures. There is no need for plumes on Venus.

LITTLE-MODIFIED IMPACT CRATERS AND BASINS

The standard model for evolution of Venus assumes the unambiguous small impact craters and basins that sparsely and randomly pock all geologic terrains to be entirely younger, likely much younger, than 1 Ga, and denies any role for older impacts. My contrary inference is that the young cratering began ca. 3.9 Ga., and that thousands of still-older preserved Venusian impact craters and basins reach 2000 km in rim diameter. Nearly all Venusian specialists regard the older structures at issue as products of plumes and related endogenic processes.

About 1000 pristine craters, with sharp rim topography and generally little-modified ejecta blankets (Fig. 3A and B), have been recognized in radar imagery (e.g., Phillips et al., 1992; Schaber et al., 1992; Schultz, 1992; Herrick et al., 1997; McKinnon et al., 1997). A searchable database is maintained by R.R. Herrick (www.lpi.usra.edu/research/vc/vchome.html), and a searchable 1998 compilation by G.G. Schaber and associates is available at http://astrogeology.usgs.gov/Projects/VenusImpactCraters. Only nine of the craters listed by Herrick have rims greater than 100 km in diameter, twenty-five are greater than 70 km, and fifty-eight are greater than 50 km. The largest of

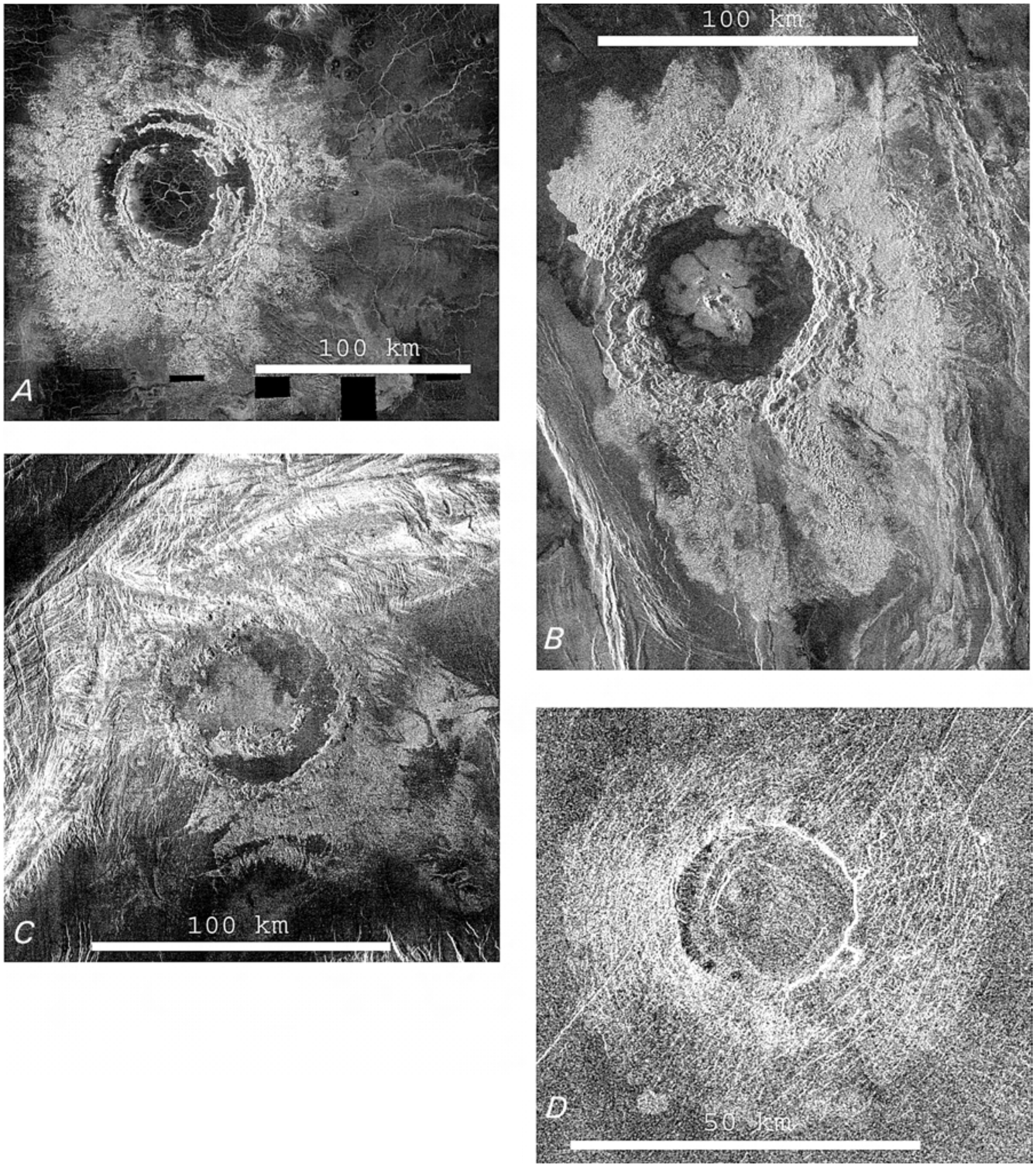

Figure 3. Small Venusian craters, illustrating false distinction between "impact" and "volcanotectonic" structures. A, B, and C are conventionally classed as pristine even though C is much eroded, whereas D has obvious impact morphology—a sharp circular rim and a slightly subdued ejecta blanket—yet is conventionally classed as volcanotectonic because only "pristine" structures are accepted as of impact origin. (A) Mona Lisa multiring crater, concentric inner ridges with lesser scarps, radial pattern in center, location ~26° N, 25° E. (B) Dickinson Crater, with central uplift, location ~75° N, 177° E. Both Mona Lisa and Dickinson have radar-dark floors (sediments or impact melt?), concentric structure both inside and outside main rim, ejecta aprons, lobate breccias, and fluidized runout flows. (C) Tilted and eroded Hepworth Crater, location ~5° N, 95° E, on SE flank of radar-bright anticlinal ridge on irregular N slope of Ovda Regio tessera plateau. Ridge stands 1 km above dark sediments of synclinal basin to SE, and 2 km above rumpled sediments to NW. North part of rim and ejecta blanket have been eroded away because of tilting S on flank of anticline. Rest of rim is degraded, and interpreted as breached by streams that flowed SSW in W, S in S, and SE in E, and that redistributed ejecta blanket, partly in lobate debris flows. (D) Sharp-rimmed crater, concentric-structured floor, and erosion-subdued ejecta apron, buried around base; location 18.7° S, 70.6° E. Mosaics, east-looking (A, B, and D) and west-looking (C), by U.S. Geological Survey.

these craters can be seen, typically as tiny dark spots enclosed in small, bright rims, at the scale of Figures 1 and 2.

Most craters and basins are circular, but many are elliptical or irregular. Many have central peak or peak-ring uplifts, and internal concentric structures. Many display much concentric fracturing, and some show ring synclines. Ejecta aprons commonly tail into flow lobes, typically radial. (Aprons on dense-atmosphere, high-gravity Venus are of groundhugging debris flows, whereas aprons on the Moon are dominated by ballistic ejecta.) Lobes flowed several hundred km from a number of structures on the plains, but not from those on bedrock uplands. I attribute this extreme fluidization to impact into thick, then-wet sediments, although the plains are conventionally inferred to consist of dry lavas. Doublet and clustered craters attest to bolide fragmentation before impact. The largest pristine basin has a rim diameter of 270 km (see Fig. 9 below), much larger than Earth's K/T-boundary Chicxulub structure and also probably markedly larger than those of Precambrian Sudbury and Vredefort.

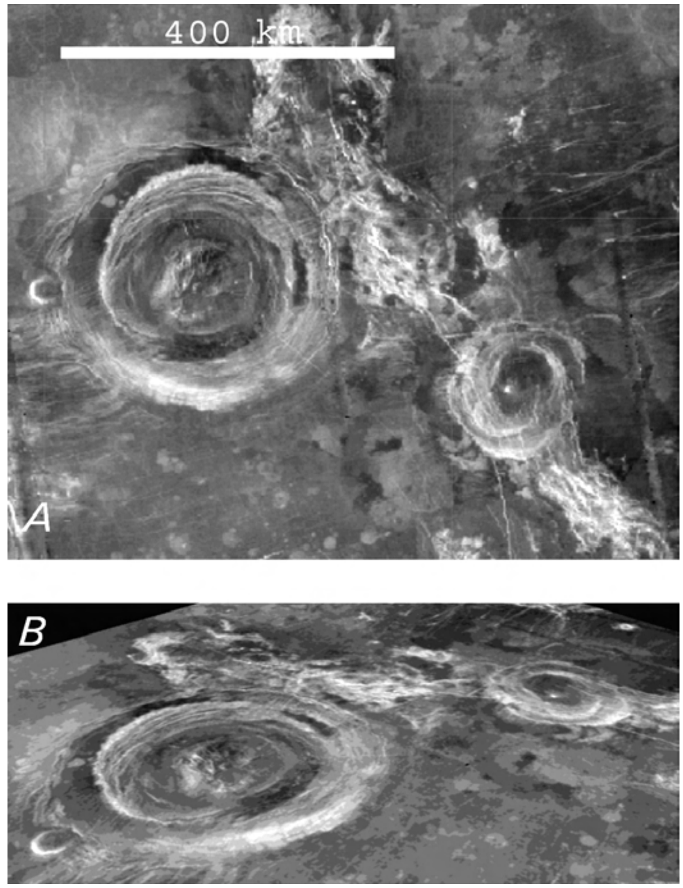

Figure 4. Radar mosaic (A) and northeastward pseudoperspective view (B) of ancient plains structures with impact morphology. Multiring Aramaiti Corona (left; 26° S, 82° E) has basin floor lower than plains; central uplift; erosion-smoothed conical ejecta apron sloping gently from rim into outer syncline; and, inconspicuous here, a broad outer rise with an outside diameter of 400 km. Multiring Ohogetsu Corona (right) also has central uplift and ejecta apron. Pseudoperspective view, vertical exaggeration 3:1, made by Trent Hare by draping radar-brightness image on digital topographic model.

Arbitrary Distinction

Most Venusian specialists agreed, even before high-resolution Magellan imagery was available, that rimmed circular structures on Venus were of unrelated young-impact and old-volcano-tectonic types. In fact, the two types intergrade—I regard the old ones as also of impact origin—and the ambiguity of the distinction has not been addressed by specialists. About two hundred of the craters accepted as "pristine" are variably deformed, tilted, degraded, and flooded or partly buried by younger materials (Herrick and Sharpton, 1999; Basilevsky and Head, 2002). The conventional basis for discriminating impact and nonimpact structures on Venus is a circular rationale: only "pristine" craters are of impact origin, and modified structures about which there is any doubt have nonimpact origins. Even some of the craters accepted as young appear to be substantially eroded (e.g., Fig. 3C; Figs. 4 and 5 *in* Matias and Jurdy, this volume), although erosion is not permitted by the standard model.

Figure 3D shows a small crater that is a bit too degraded to count as "pristine" and so, by application of the rationale that impact structures must be pristine, is commonly assumed to be endogenic. Figure 4 depicts two analogous impact basins that preserve obvious impact morphology and yet are explained endogenetically in popular discussions (e.g., Stofan and Smrekar, this volume). There are hundreds of craters and basins like these on Venus, and in turn, a complete gradation from them to highly degraded structures. Figure 5 shows neighboring young and old structures. Other figures in this paper further document the gradation between craters conventionally assigned to the young impact population and to old plumes.

Age Determination

The maximum age of "pristine" craters is deduced from chained estimates of populations of objects in Venus- or Earth-crossing orbits or in the asteroid belt, of loss of bolides to dense Venusian atmosphere, and of scaling of craters to missiles. Ambiguous final inferences are widely accepted as dogma.

There are vast numbers of tiny orbiting missiles and very few large ones, and crater sizes reflect this distribution on the airless Moon. Bolides fragment in atmospheres when aerodynamic stresses exceed bolide strength, and fragmentation is followed by dispersion, pulverization, fluidal behavior, and further retardation, which may leave nothing to strike the ground at masses and velocities adequate for crater formation (McKinnon et al., 1997). Practically all small Venusian bolides, and an arguable fraction of large ones, are destroyed in the atmosphere, which now has a near-ground density of ~65 kg/m^3.

All bolides are not created equal. The likelihood of penetration through the atmosphere increases greatly in the order: long-period comets, short-period comets, carbonaceous asteroids, stony

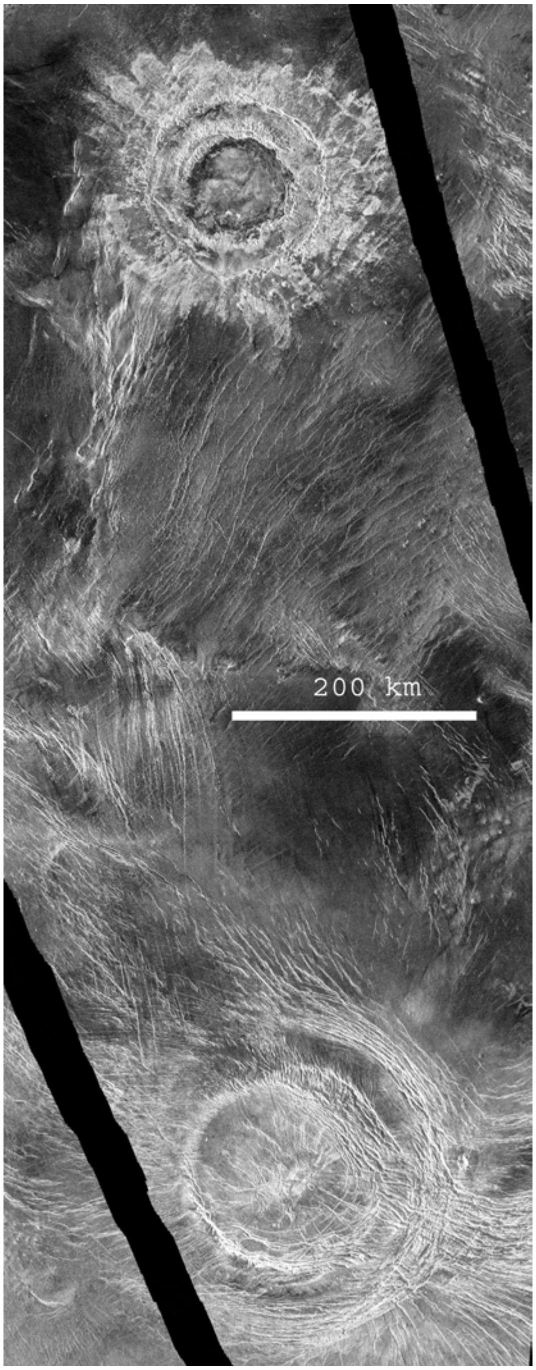

Figure 5. Old and young multiring impact craters. Meitner Crater (top) has sharp features and well-preserved lobate ejecta apron. Kamui-Huci Corona (bottom) is subdued by erosion and deposition (although its lobate apron is still visible in northeast) and is conventionally ascribed to a plume; its impact-melt(?) interior is in part higher than its rim. Black bands are data gaps. East-looking mosaic by U.S. Geological Survey of area centered on 59.5° S, 322° E.

asteroids, and metallic asteroids (Chyba et al., 1993). Small objects now in Venus-crossing orbits are overwhelmingly stones and metals, but most of these would be destroyed in the atmosphere because of their size. The rare large objects capable of producing airless-planet craters greater than 100 km in diameter —craters of the size from which Venusian flux, hence age, is primarily deduced—are mostly long-period icy comets (Shoemaker, 1994, 1998), of density less than 1 g/cm^3 and the weakest of missiles, which are unlikely to survive transit through the Venusian atmosphere.

Conventional Analysis: Young Maximum Age. The young ages to which the standard model of Venusian evolution is anchored are calculated with the assumption that the atmospheric effect was negligible on numbers, masses, and velocities of the bolides that produced large craters and basins. (All observers agree that the atmosphere filtered out small bolides; the crater-size deficit increases dramatically for diameters <40 km, and is total for those <1.5 km.) Phillips et al. (1992) and Schaber et al. (1992) deduced the no-effect cutoff to be at a crater diameter of only 30 or 35 km, and calculated a maximum age for the craters of 0.5 Ga or less. These early analyses inadequately accounted for atmospheric slowing and reduction of the effective density of large bolides, and did not scale crater mechanics for a dense atmosphere (Schultz, 1992, 1993), but nevertheless are still widely cited. No investigators have yet considered the likelihood that the early atmosphere was far denser than the present one. The atmosphere, now ~93 bars, may have been 200 or even 300 bars after evaporation of an early transient water ocean.

McKinnon et al. (1997) factored in atmospheric effects for small and midsize bolides, while acknowledging large uncertainties, and recognized that comets must account for the craters larger than 100 km. They nevertheless inferred that all incoming bolides—including fragile comets—capable of producing craters larger than 70 km had survived to do so with undiminished mass, integrity, and velocity, and from this they deduced a maximum age of the craters of ca. 0.5 or 1.0 Ga. They based their survival inference on the approximately straight line for large craters on a log size–log abundance plot. The weakness of this deduction from the small number of large craters is easily demonstrated. For their plot, McKinnon et al. (1997) binned crater diameters in increments increasing by $2^{1/2}$. I changed the positions, but not the widths, of the bins by relocating boundaries with the same $2^{1/2}$ increments but starting from 1.25 km rather than their 1.00 km. I then replotted the data, using diameters from Herrick's website tabulation (www.lpi.usra.edu/research/vc/vchome.html), and generated a curve sharply concave upward and to the right, rather than a straight line at the large-diameter end. Present data thus cannot be claimed to demonstrate a minimum size limit above which all inbound bolides survived to strike the planet—yet all popular calculations of maximum ages are locked to assumptions of such a size limit.

Alternative Analysis: Ancient Maximum Age. The limiting age of younger than 1 Ga is determined with the implausible assumption that the largest several percent of Venusian craters represent all large bolides, even the snowballs, of appropriate size that reached the top of the atmosphere. The small number and erratic size distribution of the few large craters provide no statistical support for this conjecture. Even Earth's thin atmosphere disrupts bolides to a much greater extent than is commonly assumed (Bland and Artemieva, 2003). Schultz (1993) showed that integration of atmospheric ambiguities permitted ages of 2 or 3 Ga, perhaps even 4 Ga, for the Venusian surface even without consideration of variable bolide densities and strengths, the statistical inadequacy of the small sample of large craters, and an early atmosphere denser than the present one. Paraboloid splotches in plains regions reach diameters of at least 200 km and presumably mark air-blast effects by large bolides that did not survive to produce craters (Schaber et al., 1992).

Lack of Planetary Resurfacing before Young Impacts

A corollary of the popular assumption that all pristine craters are young is that Venus was wholly resurfaced, by unearthly processes, during a relatively brief period preceding or overlapping that of the young cratering. All of the diverse speculations regarding mantle-circulation causes of such resurfacing are merely contrived rationalizations, as Kaula (1995) recognized. Nevertheless, there has been almost no evaluation of the assumptions that the pristine craters record only late planetary history and that resurfacing actually occurred. There was no general resurfacing if arguments presented here are valid.

Both Venusian plains and large low volcanic constructs are regarded in the resurfacing conjecture as of endogenic lavas. I dispute these assumptions here.

ANCIENT IMPACT STRUCTURES

Much of the surface of Venus is saturated with circular structures, from 5 to 2000 km in inner-rim diameter but most conspicuously ~100–400 km, older than the pristine impact craters and widely assumed to be endogenic. They are here argued to be of impact origin. Many of these show as variably superimposed structures in some highlands, and as variably buried structures in lowlands, as in Figures 1 and 2. Most of these structures retain impact morphology, although all are more modified by erosion and deposition than are the pristine craters agreed upon by all researchers as of impact origin. Jargon obscures published descriptions, which seldom are couched in terms the casual reader will recognize as suggestive of impact. The structures include all, or most, coronae, novae, and arachnoids in mainline reports. More than seven hundred of these large structures have been classified, hundreds more exposed large structures are ignored—and most of their ilk are, in my interpretation, buried beneath lowland sediments. A great many—thousands?—of additional small circular structures also are ignored in conventional synthesis. For example, scores of the circular structures, small to large, shown in accompanying figures go unmentioned and disregarded by standard-model proponents because they do not fit into the conceptual, impact-free pigeonholes to which those proponents restrict their attentions.

By far the most common type of large and mid-size structures has a circular rim surrounding a depression (Glaze et al., 2002; many figures of this report), as expected for impact structures. Many structures are multiring with concentric basins and rises outside the rims. The only mechanism proved capable of producing huge rimmed circular structures on solid planets is bolide impact. Venus, like the Moon, Mercury, and southern Mars, may widely preserve a surface from late-stage main planetary accretion. Specialists nevertheless almost unanimously regard the structures as young and endogenic, and do not discuss impact options.

History of Interpretation

Many of the circular structures at issue were seen on pre-Magellan radar imagery, and most early interpreters of that imagery regarded the structures as probable or possible products of impact (e.g., Schaber and Boyce, 1977; Campbell and Burns, 1979; Masursky et al., 1980; Grieve and Head, 1981; Head and Solomon, 1981; Barsukov et al., 1986; Nikolayeva et al., 1986; Basilevsky et al., 1987). Grieve and Head (1981, p. 8) emphasized that the rimmed circular features "have the gross morphology of impact craters. The larger features have a size-frequency distribution and areal density similar to craters on the lunar highlands and, if interpreted as craters, they indicate that Venus has preserved some early cratered crust." Nikolayeva et al. (1986) confirmed the size-frequency analogy to impact craters, and they, too, emphasized that these large craters might date to the main planetary accretion.

Increasingly during the 1980s, however, as terrestrial plumological conjecture inflated, most American investigators of Venus, including those who had previously inferred impacts, pressed for explanations in mantle plumes and other endogenic processes (e.g., Morgan and Phillips, 1983; Stofan et al., 1985; Schubert et al., 1989). All doubts vanished from endogenic speculations even before Magellan data were available (e.g., Senske et al., 1991; Stofan et al., 1991). Among the very few authors who mentioned reasons, Stofan and Head (1990) said, incorrectly, that the raised topography of many coronal interiors (and most are depressed; Glaze et al., 2002) is inconsistent with impact. Stofan and Head also assumed that erosion had never operated on Venus; hence impact topography could not be degraded. (Two hundred or so of the impact craters that they assumed to be pristine are now known to be degraded; e.g., Fig. 3C; Herrick and Sharpton, 1999.)

The first major reports interpreting Magellan imagery were published in the April 12, 1991, issue of *Science*—nine papers, sixty-five pages, almost fifty authors—and contained no mention of the possibility of impact origins of the circular features. Soon thereafter came fifty papers and 1100 pages in the two

1992 Magellan issues of the *Journal of Geophysical Research* (v. 97, nos. E8 and E10), which contain only one substantitive mention of possible impact origin. Stofan et al. (1992) demonstrated that the log size–log frequency distribution accords with impacts—and then rejected their own evidence in favor of plume conjectures. All interpretations in subsequent mainline papers have incorporated the assumption that the circular structures are young and endogenic.

Reasons for abandoning impact explanations have never been discussed at length in print but are obvious in assumptions, hardened into dogma by repetition, that would, if valid, preclude impact origins. These assumptions include:

1. Venus has a young surface [see prior refutation];
2. Venus has internal mobility similar to Earth's [see prior refutation];
3. Venus has no earthlike plate tectonics to dump excess heat [true], so therefore plumes must dump more heat from Venus than from Earth [non sequitur speculation];
4. The core of Venus is an inexhaustible heat source [nonsense];
5. Erosion never occurred on Venus, so impact-breccia aprons could not have been smoothed or removed [false, as discussed subsequently; furthermore, a great many aprons are preserved]; and
6. The structures at issue are most abundant in some highlands and so cannot be global [they are widely present in lowlands too but there are mostly buried].

Only a few outsiders (Hamilton, 1992, 1993, 2003b; Nikolayeva, 1993; Vita-Finzi et al., 2004, this volume) argued for preservation of ancient impact structures.

Variants. Plumes—narrow jets of hot material, rising from the core-mantle boundary to the lithosphere—are widely invoked on Earth, and plume conjectures have been transferred to Venus to explain the old rings, although the circular structures bear no resemblance to any structures attributed to plumes on Earth by even the most imaginative plumologists. Watters and Janes (1995) proposed that, to close this gap, huge circular structures should be sought on Earth (where none exist, save those known to be of impact origins) to provide evidence for terrestrial plumes.

Endogenic conjectures are unconstrained, and, in contrast to the lack of mention of exogenic options, are argued in endless detail. Hopelessly conflicting conjectures are illustrated by dimensionless cartoons or given verisimilitude by models (e.g., Musser and Squyres, 1997) wherein parameters are selected to enable desired results. Plumeheads interact with hypothetical thermal and compositional layers, spread laterally at any desired levels in the crust and mantle, and produce extension above their centers and shortening above their perimeters, or extension above their perimeters, or vast volcanic-plain eruptions, or linear rifts, or combinations of these and other effects (Hansen and Phillips, 1993; Smrekar and Parmentier, 1996; Jaeger, 2000; Krassilnikov and Head, 2003). Upward shoving by plumes or diapirs is followed by sagging upon cooling (e.g., Baer et al., 1994; Janes and Squyres, 1995); or initial uplift by a plume is followed by sagging as the plume head spreads outward (Hansen, 2002); or delamination is involved (Stofan and Smrekar, this volume). Plumes migrate beneath globally fixed crust (Chapman and Kirk, 1996), or else are fixed at depth and squirt laterally to produce multiple uplifts (López, 2002). Multiple reactivations occur (Aittola and Kostama, 2002). Megaplumes sprout miniplumes to superimpose small circular structures on large uplifts (Head et al., 1992); or miniplumes are captured by megaplumes (Johnson and Richards, 2003); or small circular structures are produced by compositional or neutrally buoyant diapirs, big ones by thermal diapirs (Koch and Manga, 1996; Hansen, 2003; Bleamaster and Hansen, 2004). Some circles may be gigantic calderas (DeLaughter and Jurdy, 1999). Great circular structures may be due to subduction (McKenzie et al., 1992). Lowlands are formed of lavas erupted from plumes (Krassilnikov and Head, 2003), yet are due to downpulling by antiplumes (Gauthier and Arkani-Hamed, 2000; Johnson and Richards, 2003), so perhaps plumes reverse to become antiplumes (Phillips and Hansen, 1998). Conflicting superplume models were proposed by Chapman and Zimbelman (1998) and Smrekar and Stofan (1999). Other endogenic conjectures include those by Basilevsky and Head (1998a,b), Brown and Grimm (1999), and Ivanov and Head (2003). Complex genetic classifications have been developed by De Laughter and Jurdy (1999), Smrekar and Stofan (1997), and others.

Earth and Moon. Evolution of opinion regarding large circular structures on Earth and Moon followed the opposite course, from endogenic to impact (see historical reviews by French, 1990; Spudis, 1996; Reimold, 2003). Majority scientific opinion long regarded the terrestrial and lunar structures now proved to be of impact origin as produced by undefined magmatic or tectonic processes.

Circularity, Rims, Multirings, and Impact Origin

No plume proponent has addressed the remarkable circularity typical of the ancient Venusian structures. The problem is evaded by ignoring the shapes, by denigrating them as "quasi-circular" or "ovoidal," or by emphasizing distorted examples. Only bolide cratering is known to produce such huge rimmed circles on planets with thick, strong exterior shells and irregular surfaces. (Crater and basin mechanics, ejecta characteristics, and impact melting relevant to understanding Venusian features are addressed by Carr, 1981; Schultz et al., 1982; Wilhelms, 1987; Melosh, 1989; Schultz, 1992; Spudis, 1993; McKinnon et al., 1997; Cintala and Grieve, 1998; and by many authors in Dressler et al., 1994.) If any of the endogenic processes instead favored by Venusian specialists operated, surface expressions would be irregular, lobate, and distorted by structural, lithologic, and topographic obstacles. Successive endogenic structures necessarily would be made less regular by interference, and could not become more circular by cookie-cutter superposition, as is the actual case.

Several specialists have told me that the multiring character and concentric fracturing of many of the large, old structures at issue are incompatible with impact origins. This conclusion is partly incorrect and partly non sequitur. Perhaps half of the old large rimmed Venusian structures and also most of the thousands(?) of small ones that seldom are mentioned do not show either concentric fracturing or ring synclines. Furthermore, despite their mantling by uneroded ejecta blankets, many pristine Venusian craters and basins also display concentric structures (e.g., Fig. 3A, B, C). Although lunar impact craters and basins are commonly surrounded by uneroded impact debris, and Martian ones by variably eroded material, multirings are obvious in both settings, particularly for rim diameters larger than 200 km (Schultz et al., 1982; U.S. Geological Survey, 2001). Precambrian Vredefort impact structure, in South Africa, is a large terrestrial example of a multiring feature.

As the figures in this paper show, the younger of the structures at issue, including the giants, are remarkably circular. They have raised rims, steeper inside than outside, and depressed floors in many cases (the exceptions can be explained by magmatic or sedimentary fills). Many are multiring. Many preserve broad exterior conical aprons, often ending in lobate runouts, presumably of impact ejecta. Where superimposed, the younger overprint the older, rather than being deflected by them. There is no sharp division between pristine and ancient craters.

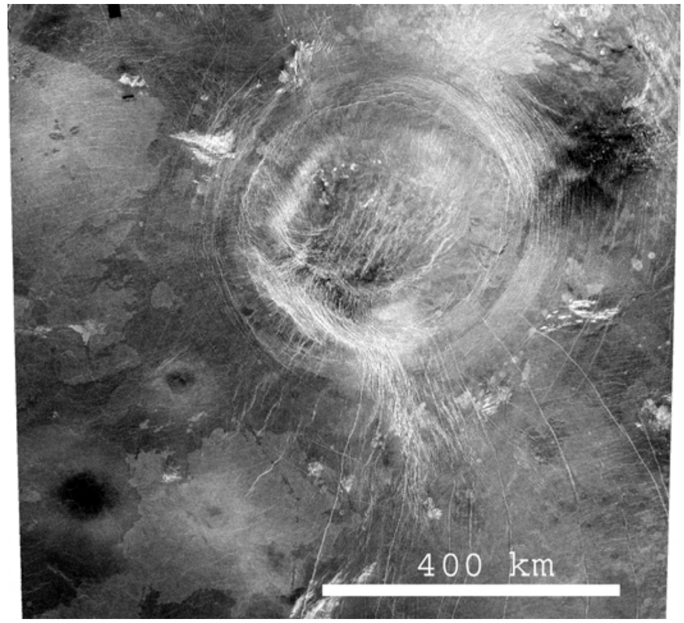

Figure 6. Fatua Corona, a mid-size ancient impact structure. Inner rim (includes the brightest arc in WNW) is its highest component and is topographically continuous, standing ~1 km above interior. Outside the rim is a shallow ring syncline, broad outer rise, and gentle apron. See Squyres et al. (Fig. 1 *in* 1992a) for topographic map and extremely exaggerated pseudoperspective image, which accord with impact origin. Outer limit of concentric fracturing is >500 km in diameter. Four small dark circles, with broad light rims, SW of Fatua may be ancient small impact craters, 20–60 km in diameter. All structures in this view are conventionally regarded as endogenic. East-looking mosaic by U.S. Geological Survey of area from 13.5° to 21.5° S and 13.0° to 22.0° E.

Description

The structures at issue are commonly circular, although many are now irregular. The accompanying images and their captions convey much of the analysis. Most of the structures preserve rims and interior basins, and many preserve exterior aprons (e.g., Fig. 7 *in* Stofan and Smrekar, this volume, which has unmentioned vertical exaggeration of perhaps 20°). Median, mean, and maximum rim diameters of the ancient craters and basins are far larger than those of the pristine impact craters.

Hundreds of the old circular structures display classic impact morphology. Their rims enclose basins and are surrounded by gently sloped conical aprons of, presumably, ejecta. The mid-sized structures of Figure 4 have low rims that face inward on basins that have a central uplift (Ohogetsu) and a central uplift plus peak-ring uplift (Aramaiti). Their gentle ejecta aprons have been smoothed by erosion and partly buried by deposition of plains material but are obvious in topography. Figure 6 illustrates a mid-sized impact structure and four small ones, all commonly classed as endogenic.

Several hundred ancient impact structures on Venus are as obvious morphologically as are Aramaiti and Ohogetsu. The reader of standard-model papers will, however, have difficulty recognizing that morphology as described in those papers, wherein impact-compatible features are minimized. Thus Stofan and Smrekar (this volume) ascribe Aramaiti to thermal upwelling accompanied by delamination of an inward-migrating ring; they neither describe its impact morphology nor account for its circularity. Among many other old structures that preserve broad, gentle outer cones of impact ejecta are the low "volcano/corona hybrids" attributed by Grindrod et al. (2004) to "buoyant mantle diapirs." The "hybrids" are impact basins (their "coronae"), with central-peak uplifts inside circular sharp rims, 100–150 km in diameter, surrounded by outward-flattening ejecta aprons ("volcanoes") 400–500 km in diameter. Even more conspicuous as a 100-km impact crater, with central uplift and a lobate ejecta apron 400 km in diameter, is Chloris Mons, termed a "large volcano" by Stofan et al. (2002).

The Venusian literature contains many pseudoperspective views of such likely ancient impact structures, but always with vertical exaggerations of 15:1 to 50:1. These distortions, often unmentioned, complicate the task of visualizing impact morphology. Basilevsky and Head (Fig. 2 *in* 1998a) presented images with very large but unspecified vertical exaggerations of six circular structures that they regarded as volcanotectonic but that to me appear to be of impact origin. Two craters are little modified. The low, even-crested, unbreached rim of one (their Fig. 2B) is 150 km in inner diameter, steep on the inside but very gentle on the outside, and encloses a flat sediment(?)-covered crater floor. A terrace at the eastern inner base of the rim may be smoothed from a slump complex. The ejecta-blanket outer slope of the rim grades into the surrounding plains. The low circular rim of the second little-modified basin (west part of their Fig. 2C) is 300 km in diameter, steeper inside than outside, has an inner-rim slump, and is narrowly breached by erosion. Its low central uplift is surrounded by basin-floor sediments(?), and a shallow ring syncline surrounds much of the rim. The other four craters (their Fig. 2A, C, and the east part of D) have circular rims with diameters near 200 km, and are varyingly breached and degraded.

Pseudoperspective images, exaggerated 15:1–25:1, of another seventeen mid-sized rimmed coronae with centered interior novae—all of them impact structures, in my view, with central uplifts, center-ring uplifts, or broad, low impact-melt volcanoes—were presented by Krassilnikov and Head (2003). Actual slopes in most of the areas shown do not exceed a few degrees, but slopes of 1° on the plots look like 20°, and hills 1 km high, with slopes of under 5° become cliffs 20 km high. Even more distorted is the depiction by Squyres et al. (1992a) of eight rimmed circular structures, mostly multiring, 300–700 km in outer diameters and each with only 1 or 2 km of gentle relief, as though consisting of cliff-sided mountains 50 km high—and they did not mention the exaggeration. The topographic maps and cross-sections of several "coronae" by Janes et al. (1992) also display impact morphology. All of these authors considered only endogenic explanations.

These and most other coronae have impact morphology. Most rims are nearly circular, and steeper inside than outside. Interiors have broad, low, centered rises that likely include both rebound uplifts and impact-melt constructs. Low parts of the interiors are commonly subhorizontal, radar-dark sedimentary(?) plains. The rims are well inside the limits of concentric fracturing, and of, where present, gentle ring synclines, anticlines, and ejecta aprons.

These structures, in varying states of preservation, saturate large areas of the planet (Figs. 7–9). Note the superposition sequences where circles overlap, and progressive obliteration of older structures (similar to that documented by Schultz et al., 1982, for Mars). The structures tend to be radar-bright, particularly conspicuous in some uplands (parts of Fig. 2; northwestern diagonal of Fig. 7; western part of Fig. 9) and fainter in lowlands (the remainders of Figs. 7 and 9; Fig. 8). The upland association is widely assumed to be genetic, and the circular structures presumed to be related to whatever extension, shortening, or upwelling is conjectured to have formed the uplands (cf. Baer et al., 1994, Aittola and Kostama, 2000; Johnson and Richards, 2003; and Krassilnikov and Head, 2003; Bleamaster and Hansen, 2004). I see the association with uplands as instead one of exposure. The structures are numerous in the lowlands, but there most visible ones are partly buried by what I regard as sedimentary strata, so I infer near saturation of subsedimentary surfaces. The structures are mostly lacking on young igneous uplands that are argued subsequently to be products of large-impact melts.

Plains exposures of ancient impact structures are sporadic. Over sizeable regions, only isolated or clustered structures extend above the surface. Some structures are almost entirely exposed (e.g., Fig. 4), most are partly buried, many protrude only as parts of rims, and some can be inferred only from the compaction of plains materials into them. Where structures overlap, impact-superposition sequences are shown (Figs. 10–12). There is no boundary between products of unrelated processes within this spectrum of variably modified structures. The obvious contrast between ancient and pristine impact structures is the variable smoothing of rims, and smoothing or loss of ejecta, of the former. That this loss was primarily by erosion, which also removed

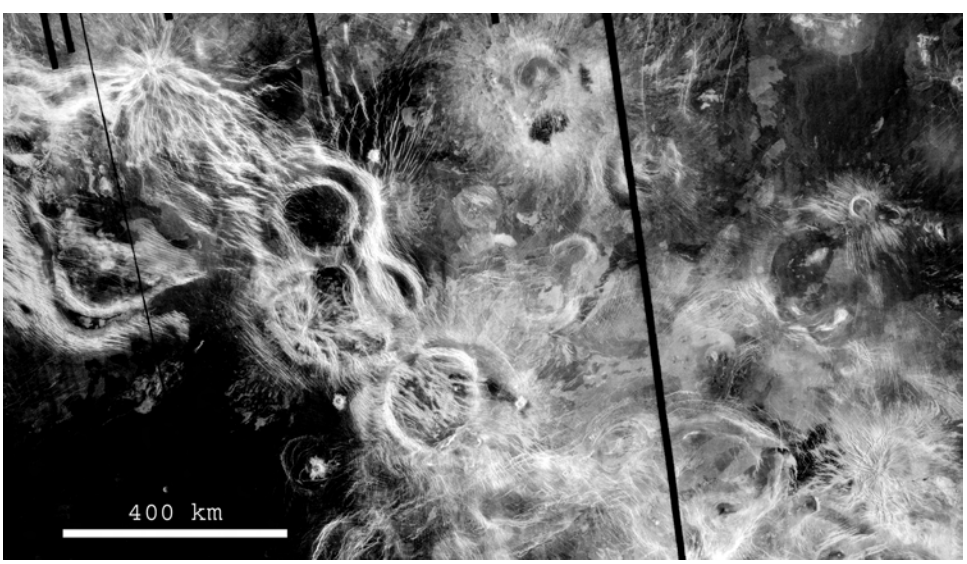

Figure 7. Terrain saturated with ancient impact structures, Themis Regio. The only conventionally recognized impact craters show as four tiny white splotches, 2–3 mm in diameter as printed. All other circular structures, bright in uplands and fainter in lowlands, are commonly regarded as endogenic but are here inferred to be impact structures. Larger structures are variably superimposed and degraded, and, in lowlands, variably buried, but many preserve obvious impact morphology; for example, the 90-km low-contrast crater with central-peak uplift, surrounded by ejecta blanket, at center of N edge. Area extends from 26.3° to 35.5° S, and is centered on 279° E. East-looking mosaic by Jet Propulsion Laboratory.

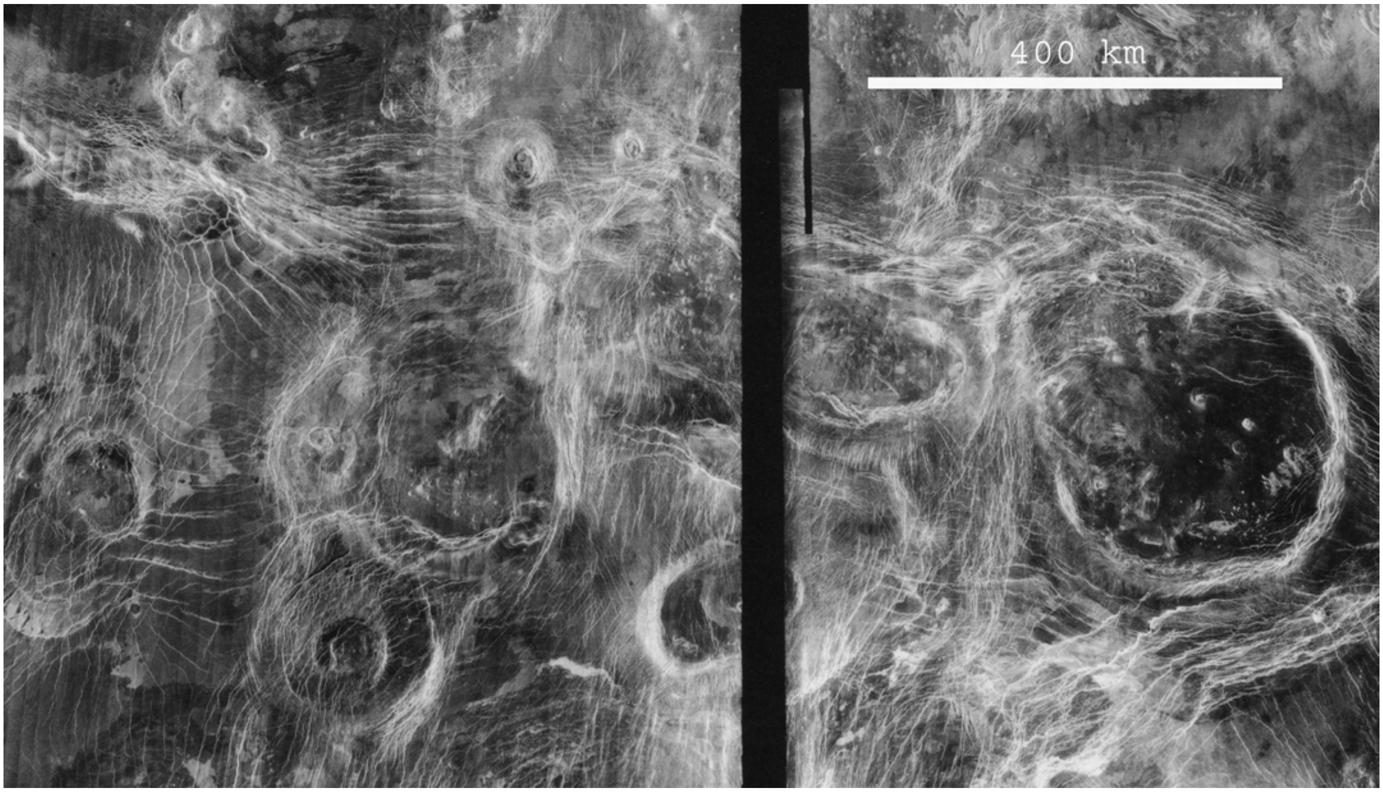

Figure 8. Terrain saturated with ancient impact structures, Ganiki-Kawelu Planitiae. Ki Corona (E-center) has 300 km diameter rim, steeper on inside than outside and 1 km high, that retains ejecta blanket to E and S and is cut by 65-km crater in N. The many other apparent old impact structures, with rims from 15 to 200 km in diameter, show varying superpositions and preservation. All circular structures in this view are here regarded as of impact origin, but only tiny Yerguk Crater, which shows as a 2-mm light spot just inside WSW rim of Ki, is commonly accepted as such. Area extends from 40° to 47° N and is centered on 222° E. East-looking mosaic by Jet Propulsion Laboratory.

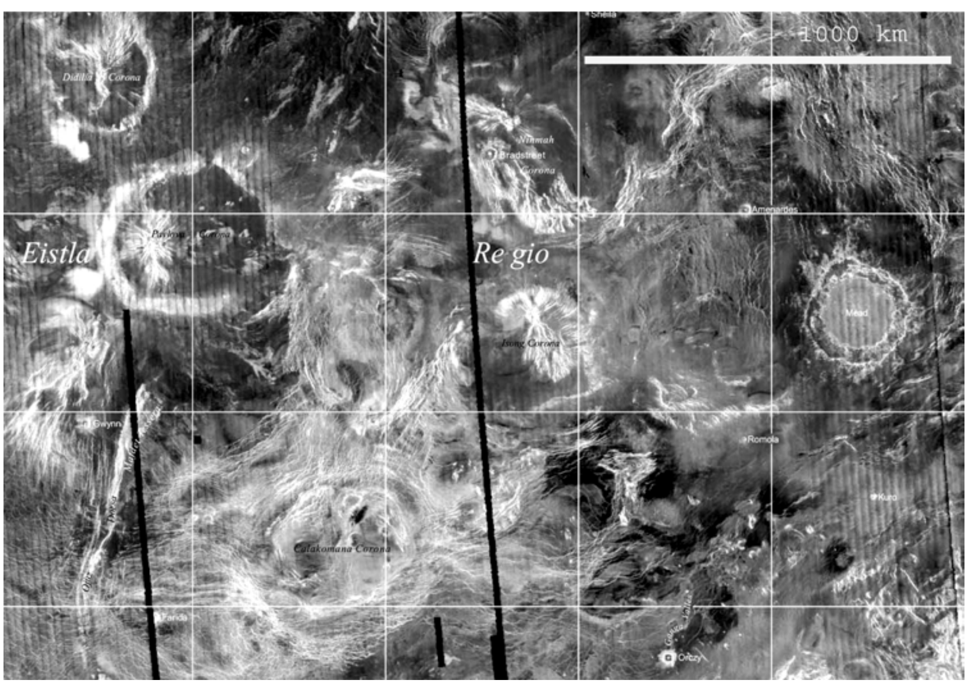

Figure 9. Young and ancient impact structures of Eistla Regio. Multiring Mead Crater (right center; outer-rim diameter 270 km) is the largest impact structure on Venus according to conventional interpretation; the only other accepted impact structures in this area are eight tiny craters. All other circular structures are conventionally regarded as endogenic but are inferred here to be ancient impact structures. These include coronae (Didilia and Pavlova, and more-degraded Calakomana and Isong, all of which retain topographic rims and are larger than Mead); the subdued 200-km rim midway between Pavlova and Isong; the semicircular 200-km rim W of Sheila; the 40-km crater, with preserved ejecta apron, SSE of Sheila; and incomplete rims of others. East-looking mosaic by U.S. Geological Survey of area from 3° to 20° N and 35° to 60° E; 5° grid.

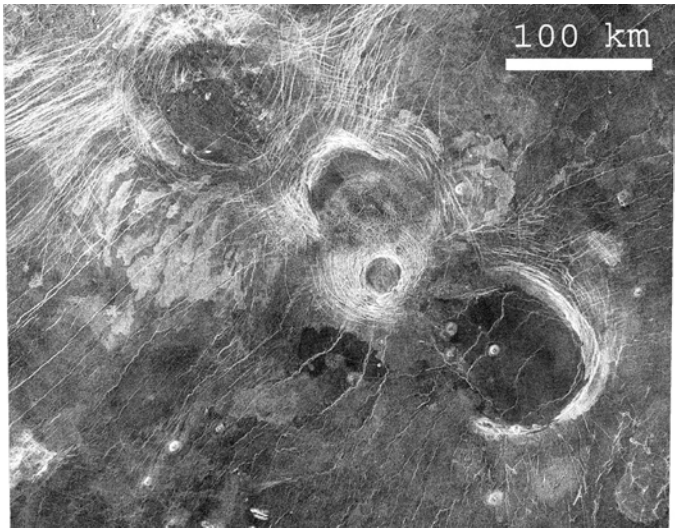

Figure 10. Superimposed ancient impact structures, variably degraded and buried, in Wawalag Planitia. Smallest (25 km rim diameter; just SE of center) is youngest, and retains sharp rim and internal crater although some of its ejecta apron is subdued. It overprints larger structures, to SE and NW, whose floors are flooded by sediment but whose half-preserved rims still stand hundreds of meters high. The NW of these three is superimposed in turn on 100-km multiring structure, farther NW, that preserves partial rim-and-crater topography and lobes to SW from its ejecta blanket. Everything in view is considered endogenic in conventional analysis, but the succession is of superimposed exogenic circles, not of younger endogenic structures deformed against older ones. Area extends from 20° to 23° S, and 211° to 215° E. East-looking mosaic by U.S. Geological Survey.

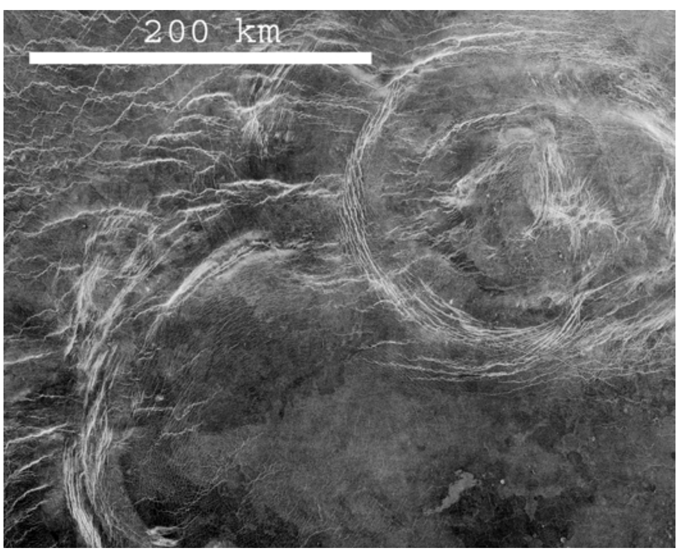

Figure 11. Superimposed ancient impact structures. The rim of Ved-Aua Corona (impact basin, upper right; topographic rim is approximately the outer ring of continuous concentric fractures) is 200 km in diameter and stands 1–2 km above irregular floor of enclosed basin. Ved-Aua is superimposed across a subdued and partly buried unnamed rim 250 km in diameter. Both are commonly assumed endogenic. East-looking mosaic by U.S. Geological Survey of area centered on ~32.5° N, 141.5° E.

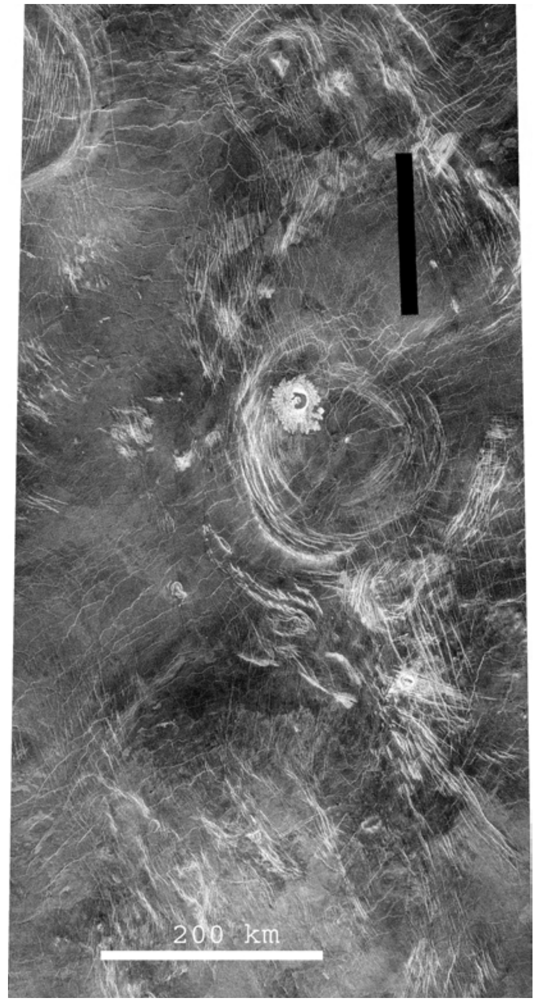

Figure 12. Age sequence of impact structures in Niobe Planitia, shown by superposed geometry and by variably subdued rims. All craters are obvious in topography, and have raised rims and low interiors, even where inconspicuous in radar reflectivity, and appear to be partly buried but revealed by topography consequent on sediment compaction. A sequence gets older northward, from SE of center: unnamed crater 50 km in diameter, with partly preserved impact apron; multiring Maya Corona, rim 180 km; unnamed structure with 200 km rim; and, at top center, Metra Corona, 180 km rim. W part of Metra contains 50-km crater with central peak; SE Metra is cut by 70-km crater. Part of multiring Eurynome Corona appears in NW corner. Old unnamed 250-km crater in S-center is almost wholly buried; compaction and draping are evidence that plains material is sedimentary, not volcanic. The only impact structures of conventional interpretation are small Horner Crater (N of center; 20 km rim) and Kiris Crater (SSE of center; 13 km); both have bright rims, dark floors with central uplifts, and light ejecta aprons. The only old structures included in “corona” tabulations are the named ones. East-looking mosaic by U.S. Geological Survey of area from 18° to 27° N and 95° to 100° E.

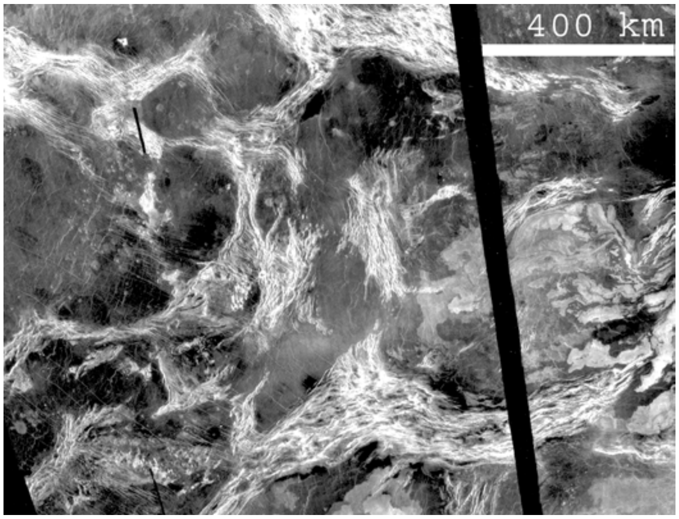

Figure 13. Network of radar-bright ridges rising <1 km above dark fill of Lavinia lowlands. Arcuate ridges may be remnants of rims of deformed impact structures but commonly are given structural interpretations. East-looking mosaic by Jet Propulsion Laboratory extends from 40° to 50° S and is centered on 352° E.

impactite from many rim synclines, and that the removed debris was deposited in low areas, perhaps mostly in a transient ocean, is discussed subsequently. In many parts of the plains that comprise most of the Venusian surface, rimmed circular remnants of impact craters and basins protrude through plains materials and show variable burial. Elsewhere, low ridges rising from plains include circles, parts of circles, and irrregular arcs (Fig. 13) that may be inherited from impact-basin rims.

Giant Impact Basins. The largest well-preserved circular apparent impact structure is Artemis, inner-rim diameter 2000 km (Fig. 14). Artemis is the large circle near the southwestern edge of Figure 2, where its gigantic ejecta apron can be seen as the gentle fan sloping far to east, south, and southwest.

Heng-O (Fig. 15; at center of Fig. 1), the next-largest well-preserved circular structure, stands in a plains region. Its inner rim, locally breached, is 900 km in diameter. The interior is flooded by sedimentary(?) materials. The surrounding shallow ring syncline is ~100 km wide. An apparent ejecta blanket slopes gently outward from the southern half of the structure but is not obvious in the north. The third-largest structure, Quetzalpetlatl (partly within the red area near the bottom of Fig. 1), stands in highlands, and only part of its rim, 800 km in diameter, is exposed beneath a broad but very low volcano that covers the rest; it is discussed again in the context of volcanoes. Tapper et al. (1998) recognized, primarily based on altimetry, an additional six or seven circular structures with rims greater than 750 km in diameter.

Among still larger and deeper but much degraded circular impact basins may be Atalanta Planitia, the broad rim of which, 2300 km in diameter, stands 1–2 km above the floor. Gauthier and Arkani-Hamed (2000) ascribed the basin to a circular mantle

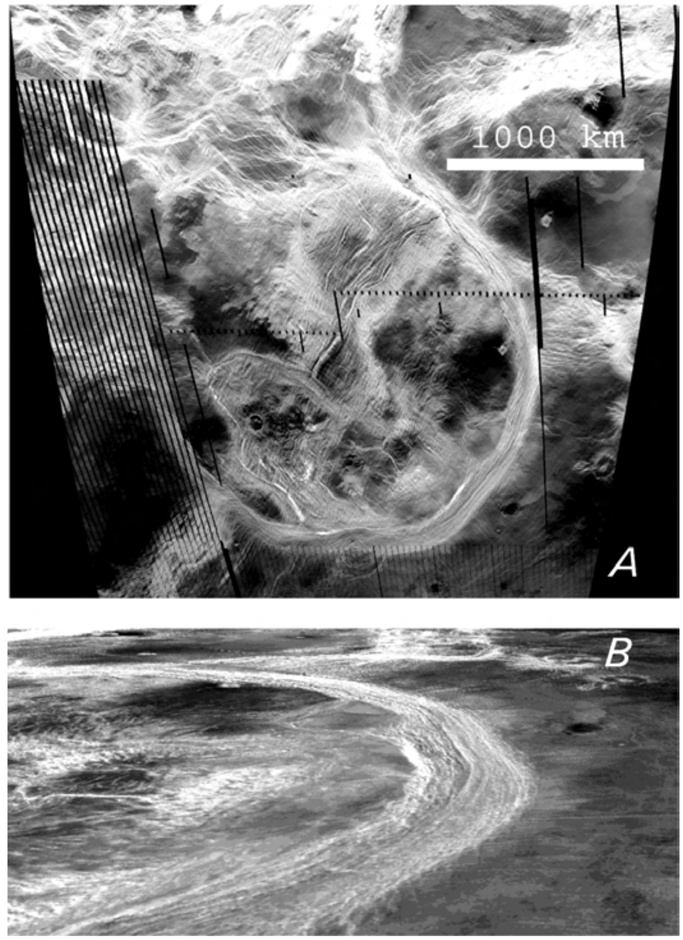

Figure 14. Artemis impact basin. (A) Radar mosaic: inward-facing rim, 2000 km in diameter, is approximately at inner edge of radar-bright concentrically fractured zone. NW part of structure is buried by younger constructs. The small doughnut at right edge, 1/5 of way up from bottom, is a central-peak 80-km impact crater; a faintly rimmed dark spot SW of it is a subdued 50-km crater; like Artemis itself, both commonly are considered endogenic, as are three larger old circular structures not obvious at this resolution (Hansen, 2002). East-looking mosaic by U.S. Geological Survey extends from 15° to 45° S and from 115° to 150° E. (B) Pseudoperspective view NE over eastern Artemis. Inner rim (passes through lower-left corner, and bright spot right of center) stands 1 km above interior. Ring syncline (most of radar-bright grooved terrain, plus half that width more into encircling radar-dull terrain, to inconspicuous crest of outer rise) is typically 200 km wide and 2 km deep (and is termed a *chasma*). Outer slope of outer rise (mostly out of view) is very gentle cone (erosion-modified ejecta blanket?) that merges, in huge lobes and with outer diameter of ~4000 km, with plain to S (Fig. 2). Vertical exaggeration 3:1; prepared by Trent Hare.

downwelling—but it is reminiscent of the huge Aitken–South Pole impact basin (rim diameter 2700 km) on the Moon and Hellas (1800 km) on Mars.

Small Impact Craters. Numerous ancient impact craters, mostly approximately 5–100 km in rim diameter, pock both plains and uplands as circular depressions and rims, many still surrounded by ejecta blankets. Examples appear on Figures 3D,

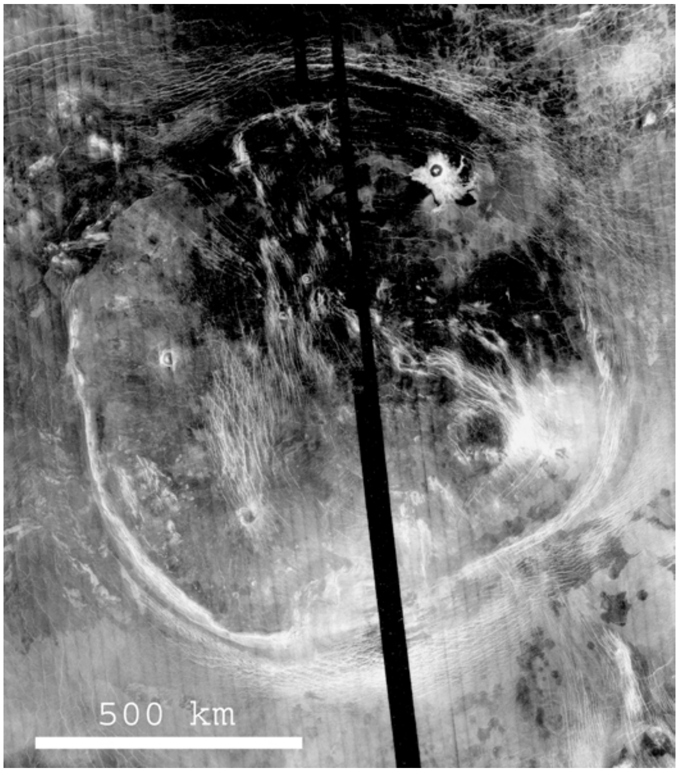

Figure 15. Heng-O Corona is a large impact basin whose rim, 900 km in diameter, rises ~1 km above both enclosed basin and surrounding lowlands. The rim, radar-bright around its S half, is topographically almost continuous around N half also. The only commonly accepted impact structure, of any size, is Hellman Crater (35-km rim, bright ejecta apron) near NE rim of Heng-O. Other structures likely of impact origin, but conventionally classed as endogenic: two small craters that show as small doughnuts (with bright, but partly buried, ejecta blankets) in SW and W-central Heng-O; the small dark crater near NW rim; degraded crater with ~75-km rim at center of Heng-O, and another just W of large bright area at center right; and other 20–80 km craters better seen on detailed imagery. East-looking mosaic by Jet Propulsion Laboratory of area from 7° N to 5° S and 350° to 0° E.

6–10, 12, and 14–16 (see also Fig. 19 below). These craters are mostly ignored by specialists. They are omitted from tabulations of young craters because they are not pristine, and so are presumed to be endogenic by default. They are omitted from considerations of "coronae" because they mostly lack concentric fracture systems or are not multiring. (Some larger members of the ancient-impact clan that also lack conspicuous fracture systems are, however, classed as "ghost" or "stealth" coronae.) These uncounted small, ancient craters are markedly more abundant than are pristine impact craters on the F-MAP images in my files, so I infer that there are several thousand of them on the planet.

Superposition Indicates Impact Origins. Younger circles are superimposed on older like cookie-cutter bites (Figs. 7–12). This superposition is powerful evidence for impact origins. Conversely, the superpositions, which are never addressed by proponents of endogenesis, are incompatible with all variants of endogenic hypotheses, for any rising or spreading magmatic or diapiric materials would produce interference patterns against preexisting structures.

Saturation. Several Venusian specialists have told me that it is absurd to say that any part of Venus is "saturated" with old circular structures, whatever the origin of those structures. Nevertheless, many regions look like those in Figures 7, 8, 9, and parts of 16 (see also parts of Fig. 19 below).

Power Law Size Distribution Indicates Impact Origins. The size-frequency distribution of ancient rimmed circular structures on Venus is as required by impact origins. Several pre-Magellan investigators recognized this in early data but then, with the notable exception of Nikolayeva (1993), disregarded it as plume speculations became fashionable.

Coronae—defined, loosely, as large ancient circular structures with strongly concentric components—fit log size–log abundance straight lines above a minimum-size cutoff (Fig. 10 *in* Stofan et al., 1992), consistent with impact. Both subdued and well-preserved structures fit about the same lines, attesting to their related origins. Stofan et al. depicted the straight-line relationship as holding for diameters down to ~225 km, whereas smaller structures, down to the minimum diameter they considered of ~60 km, fall progressively farther below the line. They rejected the impact significance of their data because, they said, the unambiguous young impact craters fit a power law distribution down to much smaller diameters. This rejection rationale is invalid both because no power law distribution has been established for pristine craters, as discussed previously, and because the quite different measurement conventions used for the two families of circular structures exaggerate the size of the older. The cited diameters of pristine impact craters are measured to inner crests of sharply defined crater rims. Diameters of the ancient structures are measured instead to inconsistently defined outer limits of concentric deformation—to outer rises beyond ring synclines, or to limits of concentric fracturing, or of major fracturing. Inner rims commonly are closer to *inner* limits of concentric deformation than to outer limits in the several hundred old structures that preserve both rims and concentric fracture systems (see many figures in this report). Stofan et al. (1992) did not mention either rims or inner diameters, but their outer-margin diameter of 225 km corresponds typically to an inner-rim diameter of 100 or 125 km. The larger-sample statistical analysis of the ancient structures by Glaze et al. (2002) also reported only outermost diameters. Glaze et al. considered only speculative endogenic origins and presented no log-log analysis, but did confirm that the better-preserved and the much degraded old structures have similar size distributions. Vita-Finzi et al. (this volume) show further that the various morphological types into which classifiers split coronae all have similar size distributions. Vita-Finzi et al. recognize the structures as of impact origin, but they too use the outer-limit convention of diameter measurement.

Stofan and Smrekar (this volume, p. 850) state that "The nar-

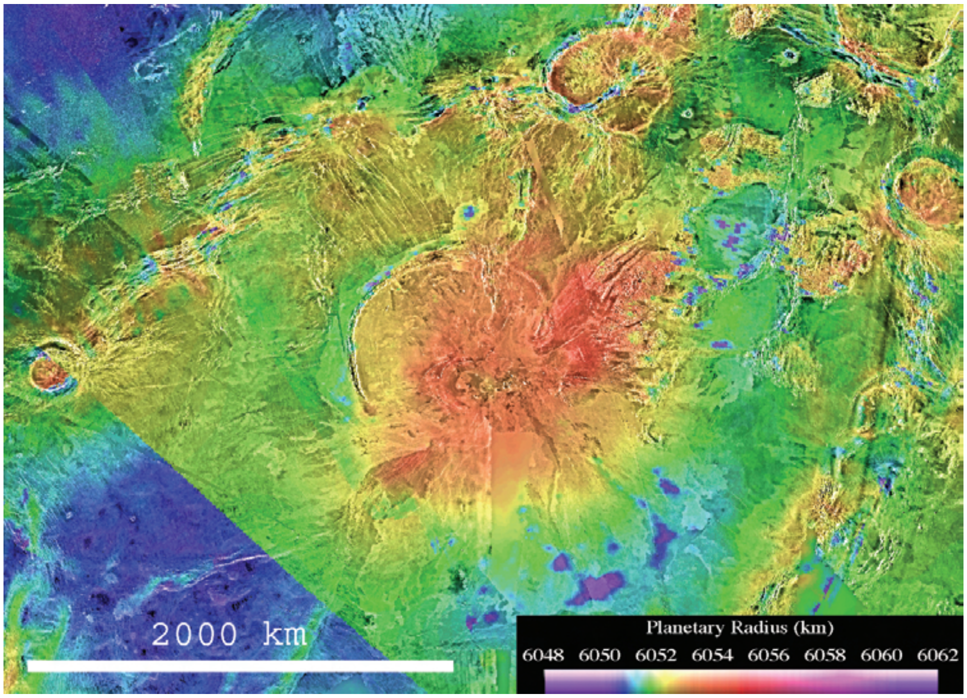

Figure 16. Quetzalpetlatl impact basin (center). Sharp basin rim, 800 km in diameter, is exposed in NW but buried beneath huge low volcano in SE. Ring syncline, maximum depth ~1 km, and outer rise surround W rim. An ejecta apron extending to 2500-km diameter is inferred. Irregular, eccentric volcano rises 1–2.5 km above rim, has slopes mostly <3°, and may be product of impact melting. Three pristine impact craters, rim diameters 25–70 km, lie N and NE of Quetzalpetlatl. Numerous larger rimmed circles are here regarded also as impact structures but, like Quetzalpetlatl itself, commonly are attributed to plumes and diapirs. Of these, the N-center circle (rim diameter 500 km) is distorted, hence older than Quetzalpetlatl, whereas undistorted W-center one (inner rim 200 km) looks younger. Straight-line color mismatch marks data set change. Polar stereographic projection, 0° longitude is vertical through center, north at top, center of image ~68° S, image by U.S. Geological Survey.

row size range and distribution of coronae are inconsistent with an impact origin." This "narrow size range" is merely a function of their consideration, not of all ancient circular structures that might be of impact origin, but only of that subset that fits their narrow definition of "coronae." They omitted thousands(?) of small, ancient Venusian circular structures, such as appear in many figures in this report. They also omitted very large rimmed structures, like Artemis, because they assign different speculative origins to those than to mid-sized structures. They also omitted hundreds of mid-sized circular structures that fell outside their definition of "coronae," including many unnamed structures shown in figures in this report. The "distribution" part of the Stofan and Smrekar argument refers to the relative scarcity of "coronae" in many plains areas and on "tessera" plateaus; I consider these tracts to have formed late in the accretionary era recorded by most "coronae."

Interpretations of cutoff diameters should not assume an atmosphere of constant density with time, hence a constant effect on bolides, for the atmosphere likely thinned greatly with time and had much more effect on old bolides than on young ones. Although cutoff rim diameters have not yet been demonstrated for either young or ancient structures, there may be a gradation between them.

Age

Huge impacts on the Moon ended with dated Imbrium Basin, and similarly preserved Orientale, ca. 3.85 or 3.90 Ga. Whether these were part of a "late bombardment" or were the last major bolides of exponentially decreasing main accretion (as argued by Haskin et al., 1998; Schmitt, 2001; and Hamilton, 2002), the same approximate age limit presumably applies to huge impacts on the inner planets. The well-preserved great impact basins—Artemis, Heng-O, and Quetzalpetlatl—of Venus are thus likely to be at least 3.85 Ga. These structures are not internally saturated with lesser impact craters and are relatively little eroded, so they formed late in the accretionary period.

IMPACT MAGMATISM

Large extrusive igneous masses of Venus are unlike anything now forming on Earth and may be products of impacts, not of endogenic magmatism. Although the small, young pristine impact craters contain only small melt sheets, many of the larger, ancient impact structures (as here interpreted) enclose major igneous features. I also attribute still larger magmatic constructs, the "tessera" plateaus, to impacts.

Shock melting is augmented by decompression melting for large structures (Jones et al., this volume). Huge magma lakes, with volumes exceeding those of their transient craters, are to be expected where those craters exceed 400 km in diameter (equivalent to final impact basins 900 km in diameter) on earthlike planets (Grieve and Cintala, 1997). Upwarping of isotherms beneath isostatically rebounding cavity floors may induce secondary mantle circulation and delayed melting (Elkins-Tanton et al., 2004).

Many large high-velocity bolides may have generated enough melt to bury their craters and basins beneath low volcanic constructs. Although a transient crater records excavation of material and its distribution in a surrounding region, hence net loss of shallow material, the generation of melt both enhances inflow of new mantle material and produces low-density final shallow columns.

Large Volcanoes—Impact Melts?

Venus has many quasi-circular broad, low apparent volcanoes approximately 100–1000 km in diameter. Brian et al. (2003) counted 134 of them. They always are given endogenic interpretations (e.g., McGovern and Solomon, 1998; Basilevsky and Head, 2000; Stofan et al., 2002; Stofan and Smrekar, this volume) but may instead be products of impacts. They are scattered randomly about the planet and do not form chains or clusters. Even the few within probable rift systems are quasi-circular, not elongate, and do not define chains (e.g., Fig. 4E *in* Head et al., 1992; Stofan and Smrekar, this volume). The rift zones record only minor extension (Connors and Suppe, 2001), so the presence of a few volcanoes in or adjacent to them is likely coincidental.

Most Venusian volcanoes are approximately circular, have radial flow patterns, and lack rift zones. Almost all are simple single-peak masses (Brian et al., 2003). Many have broad, shallow summit depressions, most of which are much larger, yet shallower, than terrestrial calderas (Krassilnikov and Head, 2004). I take the contrast to indicate the Venusian depressions to have formed above large, thin underlying magma chambers, as expected for impact-melt constructs. The large volcanoes typically have broad, flat central domes or cones and still-gentler aprons of lobate flows. Most are less than 1 km high, and slopes commonly are less than a degree or two (e.g., Dufek and Herrick, 2000). Few rise more than 2 or 3 km, although many steepen modestly toward domiform or conical summits with maximum slopes commonly less than 4°. (The latter look like gigantic cliffs in exaggerated pseudoperspective figures, such as those of plate 1 *in* Head et al., 1992.) The highest volcano is Maat Mons (1° N, 195° E), whose summit is 8 km above mean planetary radius; it straddles the edge of an upland, above which it rises only approximately 3 km, although is 6 km or so above its base on the lowland side. The main edifice is approximately 300 km across, and has a maximum slope of only 6° or so, but low-gradient flows go out as far as 400 km on the lowland side. The layered slabs imaged by Venera 9 (see Fig. 21 below) probably are on a colluvial volcanic hillside.

Terrestrial volcanoes are far steeper and higher, much smaller in diameter, and more complex. Earth's largest volcano, Hawaii, is a composite edifice (unlike simple Venusian volcanoes, it has five major centers at its present above-water surface) that rises 8 km above a base only 200 km across. Venusian volcanoes also are unlike terrestrial flood-basalt fields because the latter come from fissure systems and do not represent single giant volcanoes. The statement by Stofan et al. (2002, p. 2) that "the gross morphology . . . of the venusian volcanoes [is] similar to that of terrestrial volcanoes" is incorrect.

The circular rims of many ancient Venusian impact basins enclose flat, low cones, up to approximately 300 km in diameter yet commonly less than 1 km high, mostly central but often eccentric, that appear to be volcanoes. For many illustrations, see Roberts and Head (1993), Basilevsky and Head (2000), Aittola and Kostama (2002), Krassilnikov and Head (2003), all of whom applied the term *novae* both to these volcanoes and to nonvolcanic central-peak or central-ring uplifts (features characteristic of impact structures, although not so acknowledged in the specialist literature). Many of these volcanoes are confined to impact basins and tail out in lobate flows. Others extend to, and are dammed by, the rims, and lobate flows locally extrude through gaps. That the volcanoes are broad and very low, and have extremely gentle slopes, is obscured by the extreme vertical exaggerations of the profiles and pseudoperspective images with which they are illustrated in published papers. Conventional analysis that relates basins and volcanoes to plumes has yet to address the circularity of the basins, which of course is as required by impact origins. Many other volcanoes flow out over circular rims. Still others have broadly circular outlines, suggestive of complete burial of impact structures in which they were generated.

The largest volcano superimposed on an exposed ancient impact structure is eccentric to Quetzalpetlatl basin, which has a sharp rim 800 km in diameter (Fig. 16). The volcano is contained in the northwestern half of the basin rim, but overflows and buries the southeastern half. The volcano has one crest centrally in the basin, and a second, higher crest just inside the projection of the rim on the east. (See Ivanov and Head, 2003, for an endogenic explanation.)

A transition between exposed-rim and buried-rim volcanoes is given by volcanoes through which buried rims are visible in topography. Thus Tuulikki Mons (10° N, 275° E, illustrated by Fig. 4A *in* Head et al., 1992), is a circular single-peak volcano, 500 km in diameter but only approximately 1.5 km high. The northeastern half of the volcano flows over a step, circular in plan and conspicuous in topography (U.S. Geological Survey, 1998), that has a 200-km radius about the same center as the volcanic peak. Overfilling of an impact structure is inferred.

The well-preserved volcanoes are pocked by pristine impact craters, but in no case are saturated by ancient structures. Their age can be argued to be approximately that of the large, late impact basins of the ancient family (my general preference) or to be younger (likely true of some). Instead, Herrick (1994), Namiki and Solomon (1994), and Price et al. (1996) argued that many of these volcanoes have less than their share of pristine impact craters and thus may have formed during the period of young impacts, but Campbell (1999) showed that the nonrobust statistics do not require this timing.

Degraded large possible impact-melt volcanoes, mostly undocumented, likely go far back into the accretionary history of Venus and are represented by ill-defined rises. Brian et al. (1999) described two adjacent much degraded broad, low volcanoes, Atanua (not "Atuana") Mons and Var Mons, ~700 and 1000 km in diameter, respectively, that are overprinted by rimmed circular coronae. Hulda, largest of these overprinting impact struc-

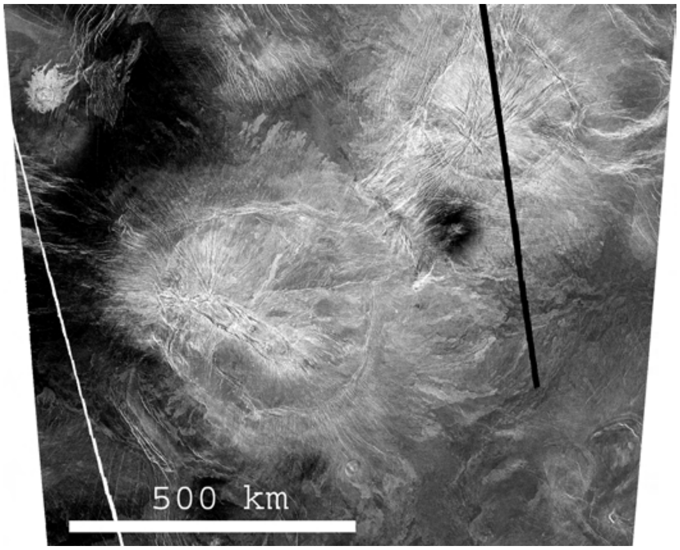

Figure 17. Impact-melt plateaus, intermediate between impact-basin volcanoes and "tessera" melt plateaus. Large, thin pancake volanoes, centered on each of two basins, breached and overflowed their basin rims, and have subhorizontal surfaces 1 km or so above nearby lowlands. Segments of circular rim, 350 km in diameter, of Shiwanokia impact basin ("corona"; extends from center halfway to SW corner) show through 400 × 600 km plateau (radar-bright plus midtones). Much of circular rim, 250 km in diameter, of Shulamite Corona (bisected by no-data line in NE quadrant of view) shows through plateau 400 km in diameter. Both rims are obvious in topography. Partial rims of older large impact structures show in S and NE. Nothing in view is conventionally regarded as of impact origin. East-looking mosaic extends from 37° to 46° S and 274° to 288° E, by U.S. Geological Survey.

tures, has a sharp circular rim 200 km in diameter surrounded by a gentle conical apron of ejecta(?). Many more possible impact-generated volcanoes may form basement to some exposed impact-saturated terrains, or be buried beneath deeply filled parts of the plains. Two small plateaus interpreted as formed of impact melts, intermediate in type between impact-basin volcanoes and the tessera plateaus discussed next, are shown in Figure 17.

Tessera Plateaus—Fractionated Impact-Melt Lakes?

A number of Venusian plateaus are here inferred to have formed from crusted impact-magma lakes that spread sluggishly outward. These distinctive plateaus have deformed tessera (complex ridged terrain) surfaces typified by fold-rumpled surfaces. Their gently undulating tops commonly stand several km above nearby lowlands, and their flanks steepen outward to slopes of 10° or more where not partly buried by plains materials. They tend to be mottled radar-bright and so presumably have rough surfaces at submeter scales. They stand out on Figure 1 (below center, across the top, and at east and west equatorial sides) and Figure 2 (west-equatorial). Some are quasi-circular, some are irregular, and some are composites of several masses each 1200–2500 km in diameter. Postulates of origin in thrust faulting and subduction (e.g., Ghail, 2002), or as ancient global crust (e.g., Ivanov and Head, 1996), or by plume eruptions are argued in an extensive literature but mostly are inconsistent with the well-exposed structures that characterize the actual uplifts (review by Hansen and Willis, 1996).

The large plateaus display gravitational spreading in their outward-increasing deformation (Fig. 18) (cf. Smrekar and Solomon, 1992; Hansen and Willis, 1996; Ghent and Hansen, 1999; Hansen et al., 2000). Plateau tops show moderate deformation in diverse directions but with a tendency toward outward motion. Small, radar-dark basins (sedimentary basins, upwelling igneous ponds, or synmagmatic impact structures?) and radar-gray stripes (perhaps mostly layered igneous rocks in the plateau sections) become progressively more strung out into apparent huge but gentle folds. Ubiquitous small folds of subuniform dimensions and morphology (the wormy pattern of central Fig. 18) become tighter and more closely spaced toward and down plateau flanks, and their axes become parallel to the plateau front. Extensional structures (inconspicuous at the scale of the figure) develop at high angles to the folds, especially on plateau flanks. There is thus shortening downslope and extension alongslope. This is as required by outward gravitational spreading and is incompatible with the inward shortening assumed by many authors. The flow gradients and outward-steepening topography are reminiscent of weak terrestrial rock masses, such as continental ice sheets, rhyolite domes, and some foreland thrust belts, all of which spread outward, driven by lithostatic head.

As Hansen and Willis (1996), Ghent and Hansen (1999), and Hansen et al. (2000) emphasized, the thin-skinned style and scale of plateau-surface deformation requires a very shallow brittle-ductile transition. They further proposed that the plateaus were formed by hot mantle welling up beneath very thin lithosphere, and that the complexes are relatively old in the pre-young–craters sequence. I see this conclusion as incompatible with the great strength of outer Venus shown by the general relationship between topography and geoid, and suggest that the plateaus formed by gravitational spreading of huge, crusted, viscous impact-melt lakes with broad semisolid fronts.

Ishtar Terra (Fig. 19) includes the highest region and the steepest major slopes on Venus. It has been attributed variously to thrust faulting, subduction, mantle downwelling, mantle upwelling, and crustal spreading (Head, 1990; Kiefer and Hager, 1991b; Lenardic et al., 1991; Kaula et al., 1992; Smrekar and Solomon, 1992; Hansen and Phillips, 1995; Kucinskas et al., 1996). As it is a composite of outward-steepening tessera plateaus, each of which shows the outward tightening of spreading structures typical of such plateaus, I deduce that it instead formed by amalgamation of sluggishly spreading magma lakes. The upper part of the western plateau of the composite highland consists mostly of a huge low-relief surface, Lakshmi Planum, above which rises a rim, approximately 2 km high, that is quasi-circular in the south and west but is irregular and broken in the north and east. I presume the rim to bound an impact basin distorted by flow of its own voluminous impact melt. The initially

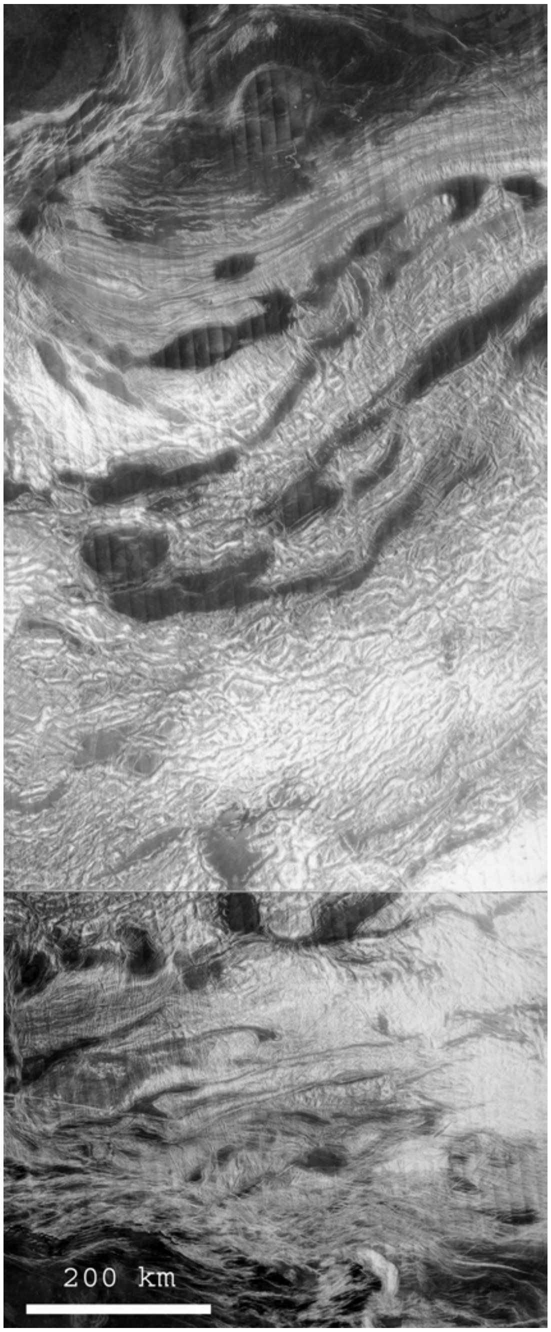

Figure 18. Radar mosaic across Ovda Regio. This radar-bright "tessera" upland rises irregularly, at slopes of a few to more than 10 degrees, 2 km or so from radar-dark plains to N and S, to undulating plateau with relief of 1–2 km. Folds are of two scales: huge folds of light and dark material, and small thin-skinned wormy, anastomosing folds. Both types become tighter, with axes parallel to contours of slope, N and S toward plateau margins. Gravitational spreading of crusted, fractionating impact-melt lake is inferred. Area bounded by ~5° N and 13° S, and 78° and 85° E. East-looking mosaic by Jet Propulsion Laboratory.

circular rim was approximately 1400 km in diameter and dammed the melt sheet to south and west, where the outer slope of the rim goes to the lowlands, but the viscous melt variably deformed, overtopped, and flowed beneath the rim to north and east.

Lakshmi and the western plateau are pocked by a few small pristine impact craters, and by five ancient impact basins with rims 50–150 km in diameter. These old structures are much sparser than in the surrounding lowlands, so Lakshmi postdates most of the lowland bombardment. Other large well-preserved plateaus have their share of late pristine impact craters but generally few ancient impact structures and so, in my terms, also formed late in the main-accretion large-bolide era that ended 3.90 or 3.85 Ga. There are also many small tessera remnants showing through plains material that are cut by large impact structures of the ancient type, so these great magma edifaces extend farther back into planetary history. An impact basin with a 400-km rim is shown by Figure 20 to cut such a remnant.

The tessera plateaus mostly have smaller geoid anomalies correlative with topography than do other Venusian topographic features. They apparently are compensated isostatically at relatively shallow depths and often are termed *crustal plateaus* for this reason. My explanation for the gravity correlation is that impact melting in thick, strong upper mantle and crust resulted in decreased density of the affected column because dense mantle rocks were converted to lighter gabbro, anorthosite, and dunite.

Intermediate between these large plateaus and the impact-basin volcanoes described previously are small plateaus that appear to be formed of broad pancakes of magma, centered on the basins, that overflowed basin rims yet only partly obscured them (see Fig. 17). These subhorizontal plateaus lack the very gentle peaks of what are commonly termed *large volcanoes,* and they lack the fold-rumpled surfaces of the larger and higher tessera plateaus.

EROSION AND SEDIMENTATION

If the ancient circular structures so abundant on Venus do indeed record impacts, then the highlands of the early planet must have been eroded during the period of their accretion, and the lowlands must have received complementary sediments. Many young, pristine craters are in fact eroded and breached (e.g., Fig. 3C), which invalidates the no-modification standard model. Rims and central uplifts of even the best preserved of the ancient structures have been softened, and ejecta blankets subdued. Still older structures have lost progressively more of their ejecta and topographic character. Much impact debris was removed from highlands and deposited in lowlands. Erosion and deposition went on throughout much of the era recorded by the visible ancient impact structures, for the degree of degradation on the one hand, and burial, on the other, vary widely. Substantial erosion preceded formation of the huge, well-preserved impact structures of Artemis, Heng-O, and Quetzalpetlatl, yet erosion and sedimentation continued into the era of pristine

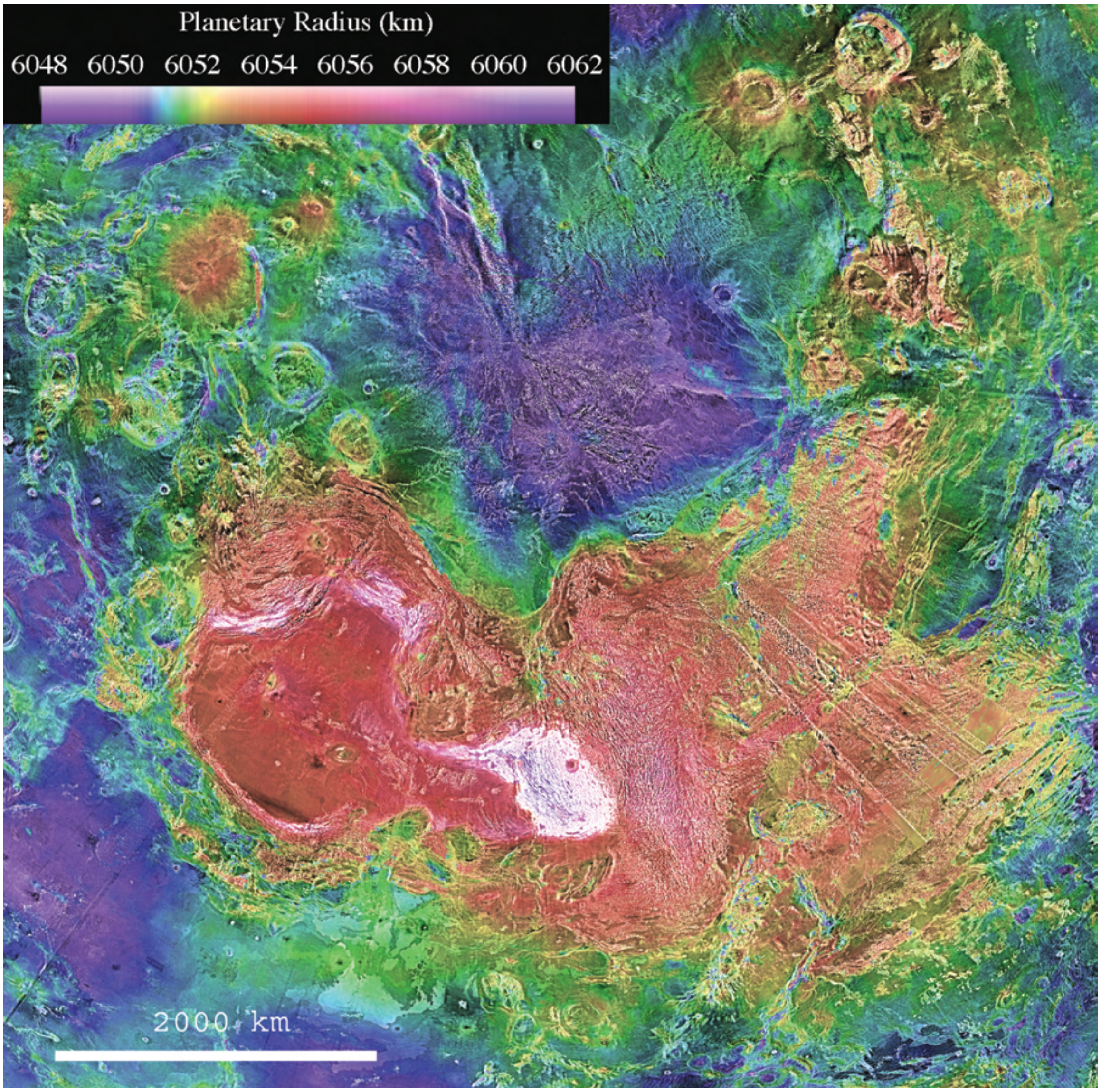

Figure 19. Ishtar Terra upland is a composite of "tessera" plateaus, interpreted as formed by outward-spreading crusted, mostly-crystalline lava lakes produced by huge impacts. Radar-bright rim of Lakshmi Planum (dark red, at center of SW quadrant) is steeper inside than outside, ~2 km higher than subhorizontal interior, and is still almost circular, ~1400 km in diameter, in S and W but is deformed and broken to N and E; it may be the impact basin in which one magma lake formed. Radar-white area (Maxwell Montes, below center) reaches 11 km above mean planetary radius. Horseshoe-shaped northward slump, 700 km wide, bounds Maxwell on N (hence may be related to its uplift) and removed much of E rim of Lakshmi. Many small bright-rimmed pristine impact craters speckle view; largest is near center of upper-right quadrant. The many circular structures (most conspicuous in W-central and NE lowlands) with rim diameters 100–500 km are conventionally attributed to plumes but are here regarded as ancient impact craters and basins. Polar-stereographic projection; vertical midline is longitude 0° (bottom)–180° (top); N pole is ~1/3 of way down from top of figure. Image by U.S. Geological Survey.

impact structures, for the breccia aprons of many of these structures are overlapped by plains materials (Collins et al., 1999).

The resurfacing postulated in the standard models to have preceded the relatively pristine impact craters was primarily by erosion and sedimentation, not by magmatism and tectonism.

Atmosphere and Hydrosphere

Water must have been voluminous early in Venusian history, and subsequently lost, for water-free accretion is impossible. Venus has no bathtub ring of features to suggest a long-stable

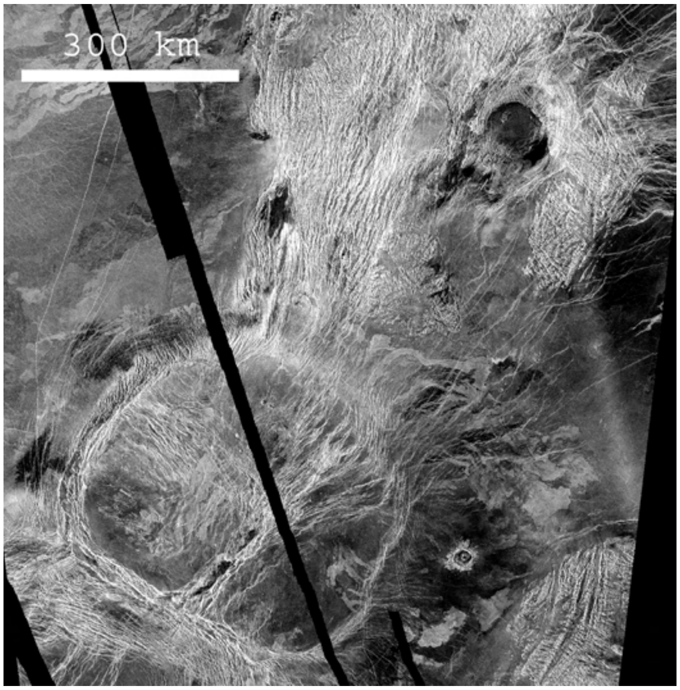

Figure 20. Remnant of old tessera plateau, flanks covered by plains material, cut by ancient impact basin. Lhamo Tessera (fold-ridged terrain trending SSW to center) is cut by impact basin (Eithinoha Corona) with 400-km rim that stands as high as 2 km above surroundings and 1 km above basin interior. Conventional interpretations accept as impact structures only young mid-size Hsueh T'ao Crater (dark floor, in NE quadrant of image) and tiny Guilbert Crater (light apron, SE quadrant). East-looking image, centered on 55° S, 10° E, by U.S. Geological Survey.

shoreline, but the planet may have had a fluctuating ocean. The present 93-bar greenhouse atmosphere consists of approximately 96.5% CO_2, 3.5% N_2, and traces of many other gases, including water, and distributes heat smoothly around the planet (ground-surface temperature is near 475 °C), but this state reflects the present evolutionary stage and the temporal increase of solar luminosity. Evaporation of a hydrosphere in a runaway greenhouse, followed by loss of water by reaction (as dissociation followed by oxidation of CO to CO_2), and by rapid removal of H by the solar wind in the absence of shielding by a planetary magnetic field, is likely (Donahue et al., 1997; Lundin and Barabash, 2004). The D/H ratio in the atmosphere, approximately 150 times that of Earth, accords with this explanation (Hunten, 2002).

Sediments Seen by Landers

Soviet landers transmitted scanner images of the Venusian surface (Fig. 21). The flaggy or laminar outcrops of the plains (Venera 10, 13, 14) would be gray in unfiltered sunlight. They appear to be of lithified sedimentary strata, and were so interpreted by most pre-Magellan Soviet observers. Basilevsky et al. (1985, p. 144) suggested that the layered rocks were deposited from turbid flows in dense atmosphere, and that "subsequently, these fines were lithified, and the environment changed into one permitting disintegration of the lithified material, but with essentially no transportation." Basilevsky and Head (2003, 2004) argued that the layered materials are airborne ejecta from young impact craters, and that the plains are formed of overlapping deposits of such material. Most Venusian specialists, however, now assume the illustrated rocks to be mafic lava with puzzling laminar structure.

Aqueous Erosion and Deposition

None of the Venusian highlands (e.g., Figures 16, 18, 19) display obvious major integrated valleys. This paucity apparently precludes any prolonged period of substantial rainfall since those uplands formed. Nevertheless, many local systems of integrated gullies and shallow valleys that drain parts of Venusian uplands look like products of aqueous erosion (Baker et al., 1992, 1997; Komatsu et al., 1993, 2001). Because the Venusian surface is now too hot for liquid water, and the atmosphere is essentially anhydrous, Baker et al. and Komatsu et al. dismissed aqueous erosion and appealed to subsurface magmatic processes related to plumes. Others attribute the erosion to thermal or mechanical effects of lava flows. Only Jones and Pickering (2003) have argued directly for ancient aqueous erosion of valleys and their channels.

A "young" impact crater, tilted and variably eroded in what appears to be aqueous fashion, is shown in Figure 3C. Some radial systems of purported fractures and dikes in the old impact structures and in broad, low volcanoes are largely systems of downhill gullies that diverge from radii in the local downhill directions. Many of these small valleys may be erosional, not structural or magmagenic, and may relate to sedimentary depositional systems in adjacent lowlands. Thus Mbokumu Mons (Fig. 7A and C *in* Krassilnikov and Head, 2003; they gave structural explanations) can be interepreted in terms of impact, erosion, and sedimentation. The subdued but nearly continuous radar-bright impact-basin rim, approximately 200 km in diameter, encloses variably sedimented radar-dark lowlands from which rises an off-center uplift. Very gentle outward slopes surrounding much of the rim may be an impact-ejecta blanket with an outer diameter of 500 km. Shallow valleys draining the uplift are downslope rather than radial. Most of the valleys feed long lobes of sediment in the intracrater lowlands, beginning abruptly at the slight slope break at the base of the upland, and some of these lobes continue down the outer apron in much of the southeastern quadrant, where the sediments overtop, or rework, the thinly-buried rim. In the northwestern quadrant, where the off-center uplift is close to the rim, the erosional valleys continue directly across the breached rim and feed sediment lobes on the outer apron.

The surface of Venus is dominated by low-relief plains with low radar reflectivity indicative of a fine surface texture. Plains

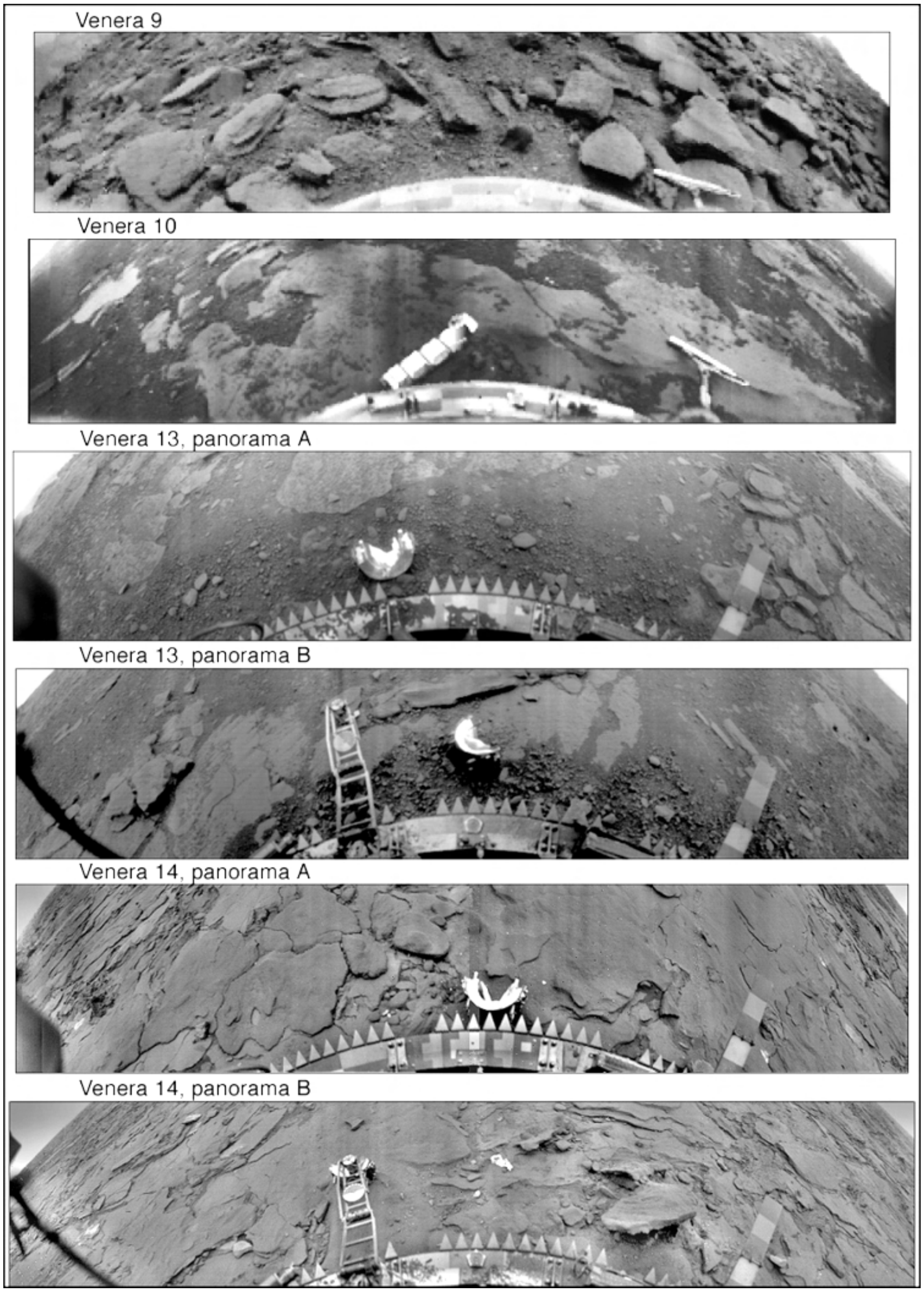

Figure 21. Scanner images of surface of Venus by Soviet landers. Venera 9: colluvial slabs of thick-layered material on slope, probably on volcano flank in NE foothills of Beta Regio. Venera 10: layered-rock plain near SE Beta Regio. Veneras 13 and 14: bedding-plane outcrops of thin-layered rock; faint striping along bedding planes suggests traction features in sediments; 14 shows gritty texture; SW part Navka plain. Compositions broadly basaltic. Venera 10, 13, and 14 images have been interpreted by most Russian viewers to be eolian sediments, but by Americans to be lava flows. Scanners inclined 50° downward from heights of ~1 m; middle part of each view is close-up, corners reach horizon. Instruments and port covers are 20–60 cm long; lander-base teeth are 5 cm apart. Described by Florensky et al. (1977), Basilevsky et al. (1985), and others. Figure provided by Russian Academy of Sciences.

material variably floods, from the outside, many otherwise pristine impact craters (as agreed by all observers), and more thoroughly floods, and in many areas largely or wholly buries, ancient impact structures (as I interpret them). Plains materials look like sediments where imaged by landers. The printing-through of buried structures (see Fig. 12) indicates plains materials to have been weak and compactible. Deformation of plains material, and superabundant mud volcanoes(?), accord with expected climatic effects on initially thick, wet sediments. Compaction and recrystallization of sediments to dense rock is required by the high surface temperatures, now approximately 475 °C, which is appropriate for upper-greenschist-facies metamorphism, although hydrous metamorphic minerals could not form under present anhydrous Venusian conditions.

Plains are cut by many narrow sinuous channels, mostly 1–3 km wide but only 50 m or so deep, and hundreds to thousands of km long, undoubtedly formed with gentle gradients but now complicated by slope reversals due to local and regional warping (Baker et al., 1992, 1997; Komatsu et al., 1993; Komatsu and Baker, 1994; Williams-Jones et al., 1998; Stewart and Head, 1999, 2000). The channels display tributaries, braids, cutoff meanders, levees, overflows, and point bars. Some channels end in dendritic distributaries and lobate depositional systems (Baker et al., 1992). The channels commonly are ascribed to thermal erosion by superheated lavas (although there is no plausible mechanism for superheating and the cooling of even such improbable lavas would prohibit the cutting of the long channels), or are attributed to complete collapse of enormously long lava tubes. More promising is the recognition by Jones and Pickering (2003) that the meandering channels are morphologically similar to terrestrial submarine turbidite channels, and hence that the plains may be surfaced by overbank and distributary turbidites. Lobate sheets, which resemble terrestrial turbidite sheets and are as long as hundreds of km, are common on Venusian plains and gentle slopes. Although always ascribed to lava flows by specialists, they resemble terrestrial turbidite sheets. They are too thin to have reflective edges, and generally are radar brighter at incidence angles more oblique to the surface than at steeper angles, indicating the contrast to be due to dielectric differences (Ford et al., 1993, p. 110–114), not to surface roughness as predicted by lava designations.

Eolian Erosion and Deposition

Processes related to ambient winds are now only minor contributors to the landscape. Wind streaks and low dunes are widespread (C.M. Weitz *in* Ford et al., 1993, p. 57–72; Greeley et al., 1997), but the presence of pristine impact structures of great age shows erosion to be minor. Outcrops imaged by landers (Fig. 21) have little fine-grained cover—perhaps the fines are blown away—but do not appear sandblasted. Surface winds estimated from Soviet lander data reached only approximately 4–7 km/h.

Venus now has very slow retrograde rotation—its day is 117 Earth days long—and has been slowed by solar tides. Winds must have been stronger when rotation was faster. The early atmosphere may have been much denser than the present one. Saltation threshold decreases, and movable particle size increases, with both the velocity and density of the atmosphere, and the threshold at which planar beds form, as opposed to dunes and ripple, lowers (Marshall and Greeley, 1992). Subhorizontal sand sheets, such as cover areas of more than 10^4 km^2 in the eastern Sahara, would be favored if grains were not well sorted (Bagnold, 1941), as would be expected for sources in comminuted impactite.

Radar imagery of tessera plateaus, viewed in optical stereo of pairs of high-resolution images with the same look direction but different incidence angles, reveals a scoured landscape unlike any on Earth. Closed depressions are ubiquitous (but their abundance may be exaggerated by radar illusions) and mostly appear to be of scoured rock. Rock ribs dominate the scene, and even cross most of the relatively few flat-floored depressions. Violent winnowing by ancient winds in a dense and perhaps corrosive atmosphere may be indicated.

Bolide Effects

Bolide-generated atmospheric shock waves, thermal expansion waves, and windstorms likely are major agents of erosion and deposition (Schultz, 1993; Takata et al., 1995; Greeley et al., 1997). Although now rare, they must have been much more important when the ancient impact structures were forming, and may then have been augmented by denser atmosphere and a hydrosphere.

Plains Modification by Tectonism and Climate Change

Low antiforms grew before, during, and after deposition of plains materials (Parker, 1992; Stewart and Head, 1999, 2000). The plains are also deformed pervasively by small-strain structures that may be products of climatic change. These include wrinkle ridges and polygonal or orthogonal fabrics, broadly uniform in intensity over large regions, superimposed on the eroded channels as well as on surface materials (Fig. 22). Wrinkle ridges are 20–200 km long and only 1–2 km wide. These features generally are taken to indicate endogenic-tectonic shortening and extension (e.g., Squyres et al., 1992b; Bilotti and Suppe, 1999), but more likely reflect changing climates as the early Sun brightened and the atmosphere heated (Anderson and Smrekar, 1999; Solomon et al., 1999; Smrekar et al., 2002). Limitation of climatically controlled deformation to plains materials is evidence that the plains are formed of sediments, and not of the volcanic bedrock of popular assumption.

Shield Plains—Mud Volcanoes? Several hundred thousand small, low shield constructs stud shield plains, tracts of the Venusian plains 10–700 km across (Fig. 22) (Guest et al., 1992; Crumpler et al., 1997; Kreslavsky and Head, 1999). The circular shields range from less than 0.5 to 16 km in diameter (median, 3.5 km) and are less than several hundred meters high, and most have subhorizontal tops with or without summit pits. Slopes average only ~4°, although many reach 15° or so, and are variously conical, gently concave upward, or convex. They locally coalesce. Most shields are radar dark, so their surfaces presumably are smooth at submeter scales. Larger flat-topped domes, 20–50 km in diameter and typically only several hundred meters high, and also often with central pits, occur sparsely in the shield fields (Ivanov and Head, 1999); they were long assumed to be silicic lava domes, but their radar response is utterly unlike that of terrestrial domes (Plaut et al., 2004).

These shields share no features of occurrence with terrestrial volcanoes, yet invariably are referred to as volcanoes and cited as proof that the surrounding plains represent vast lava flows, even though shallow-subsurface magma sheets with areas up to 10^5 km^2 each are implausible. The little shields are scattered randomly about likely areas of thick plains deposits, they

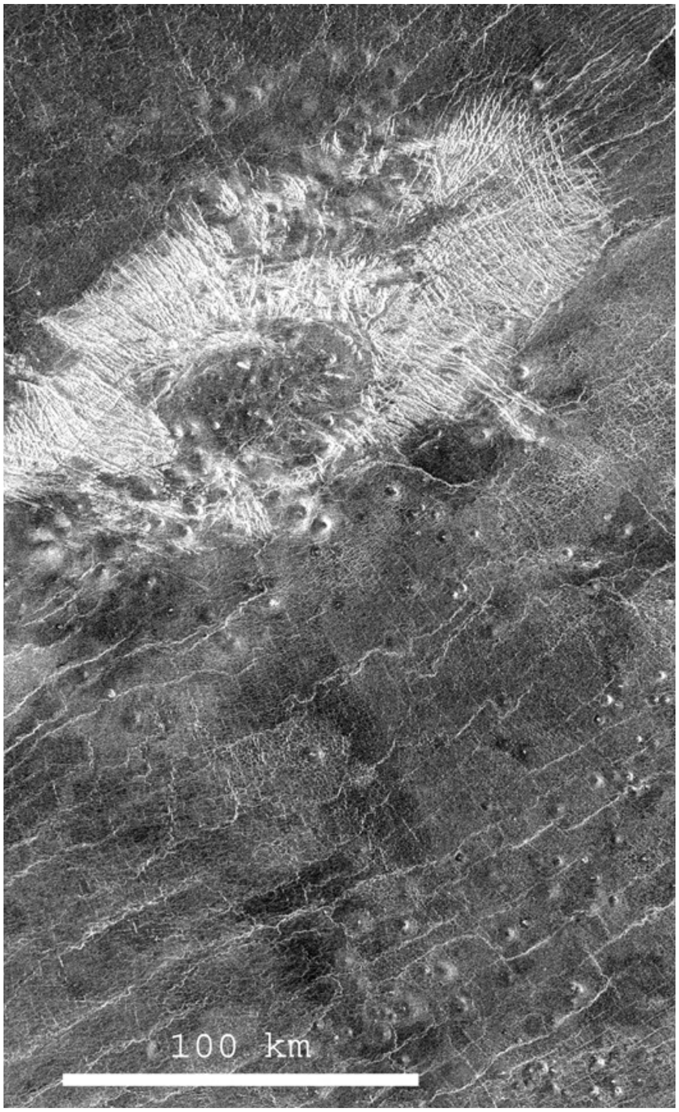

Figure 22. Plains deformation, Niobe Planitia. Apparent low, very gentle anticline (radar bright) rises from Niobe sediment plain (dark). Crest of anticline appears breached to reveal deeper and topographically lower strata (dark). Fine reticulation of plains (meshes <1 km to ~3 km, varying with area), low and narrow wrinkle ridges 10 km or so apart, and low mud volcanoes (light and dark spots, diameters <0.5–5 km) may all be responses to heating of initially wet sediments by increasing greenhouse atmosphere. The small cones show no elongation or orientation, hence no control by dikes or fractures, which is incompatible with conventional interpretation as igneous volcanoes. Area extends from 24° to 27° N and 103° to 105° E. West-looking mosaic by U.S. Geological Survey.

do not define fissure systems and are not individually elongate or fissured, and they are not related to large volcanoes. The small shields are not seen to feed the plains. (A purported exception was illustrated by Fig. 2C *in* Head et al., 1992: radar bright lobate flows [sediments?] extend out in several directions from an inconspicuous rise, 150 km wide but only several hundred meters high, on which the little cones are abundant.)

I infer the shields and domes to be mud volcanoes. Terrestrial mud volcanoes occur where water-saturated weak materials are overpressured, as in hydrothermal areas (pressurized by steam) and in accretionary wedges in subduction systems (pressurized by structural imbrication). The shield plains commonly are wrinkle ridged—inferred previously to record climatically caused thermal deformation of sediments. The mud volcanoes may record pressurizing by atmospheric heating of water-saturated sediments, perhaps after evaporation of a transient ocean; or expansion of supercritical hydrous fluid in wet sediments might have produced the mud volcanoes as atmosphere either lost pressure via material loss, or gained greenhouse heat.

Overview

The preceding inferences regarding erosion contain major ambiguities. One possible reconciliation is that dominantly eolian erosion, vastly more severe than that now operating, delivered sediment to a shrinking ocean. Major rainfall did not occur in the superdense atmosphere.

EARLY HISTORY OF VENUS

Venus likely had reached almost its full size and was fractionated by 4.45 or 4.40 Ga, and the youngest of the subsequent large impact structures formed ca. 3.90 or 3.85 Ga. The ancient Venusian upland impact structures appear to have formed on some sort of basement, not on bottomless impactite, so protocrust and impact-melt-lake crust may be present in impact-saturated uplands and buried beneath sediments and impact debris in lowlands. Venus preserves the record of accretion, with only minor resultant planetary growth, during the approximate interval 4.4–3.9 Ga.

AFTERWORD

I showed (Hamilton, 2002, 2003a) that if multidisciplinary data are substituted for a few widely accepted but dubious assumptions regarding Earth, a scenario for its evolution and behavior emerges that differs fundamentally from all variants of the standard model. In this paper, I attempt to do the same for Venus. My Venusian analysis includes the inference that thousands of ancient rimmed circular structures, 5–2000 km in diameter, are impact structures. Popular conjecture that the structures are endogenic is incapable of explaining their circularity, morphology, and superpositions, and is based on extrapolation of discredited speculations about Earth. There are no apparent sources for the voluminous lavas conventionally invoked to explain filling of vast Venusian lowlands. Venus is immobile in comparison to Earth.

Geomyths, based on dubious assumptions rather than data, are widely entrenched in geoscience as dogma insulated from analysis (Hamilton, 2002; Dickinson, 2003 [the term *geomyth* is his]). Thus, conjectures on which the original concept of plumes on Earth was based have all been disproved, yet instead of seeking alternatives, advocates evasively elaborate assumptions. Plume speculation was exported to Venus to explain features utterly unlike those for which it was devised on Earth, and was promptly accepted as dogma. William Abriel (2004, pers. commun.) speaks of "the tyranny of the anchored model"—of the common unwillingness of scientists to evaluate assumptions behind their models. The anchored models of geodynamics and geochemistry have retarded geoscience for half a century. Too often the models are further shielded (as is the case for Venus) by peer reviewers who block studies and publications that seek alternatives to their own speculations.

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Stephen Saunders allowed me to study, and gave me many prints of Magellan imagery at JPL in 1992. Robert Sucharski and Adrienne Wasserman gave me access to U.S. Geological Survey imagery in Flagstaff in 2004, and provided many prints, particularly of the large, high-resolution F-MAPs. Discussions with Leslie Blaumeister, Mary Chapman, Vicki Hansen, Robert Herrick, Donna Jurdy, Francis Nimmo, Suzanne Smrekar, and Ellen Stofan aided my understanding of mainline interpretations. The manuscript was much improved as a result of reviews by Don Anderson, Gillian Foulger, James Head, Mikhail Ivanov, Donna Jurdy, and David Stevenson—half of whom disagree strongly with my interpretations.

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