DEPARTMENT OF THE INTERIOR
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Geologic/Geomorphic and Structure Maps of the Northern Quarter of Venus

by

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MAP COMPILATION

The two sheets in this map set are the first step in a research project funded by the National Aeronautics and Space Administration (USGS Contract W15,814). The main goal of the project is to investigate the geologic evolution of Venus. The maps were a planned prerequisite to that project in order that local study areas could be placed in chronologic and regional geologic context. Because of the interest in Venus due to the Magellan Mission, the open-file format was chosen to expedite availability before imaging data begin to arrive from the spacecraft in August 1990. A map of the same region by Soviet authors (Sukhanov et al., 1989), which shows an alternative interpretation, has been published under a joint U.S./U.S.S.R. cooperative effort (Basilevsky et al., 1989).

These maps are the result of a photogeologic interpretation of images from the first medium-resolution orbital imaging radar survey of the northern quarter of Venus. The images were acquired by the two Soviet spacecraft Venera 15 and 16 in 1983-84. Except in a few small areas, previous data were insufficient for geologic mapping, allowing only general statements to be made (Masursky et al., 1980; Pettengill et al., 1980; McGill et al., 1983). The resolution of 1-2 km obtained by the Venera synthetic aperture radar (SAR) system (Kotelnikov et al., 1985) is comparable with that of images of Mars obtained by Mariner 9. The Venera SAR instrument, however, "illuminated" the surface at a constant angle (13 degrees off nadir) with 8-cm-wavelength microwave energy and recorded the backscattered albedo, whereas Mariner 9 recorded visible wavelength albedo at varying solar illumination angles. Thus, references made herein to light or dark albedo on the Venera images indicate some combination of slope, roughness, or reflectivity differences at the surface. (See Avery and Berlin (1985), Simonett and Davis (1983), and Elachi (1987) for progressively detailed discussions on radar imaging and interpretation and Ford et al. (1989) for a treatment of image analysis as pertaining specifically to Magellan data.)

The area imaged by the Venera craft (115×10^6 km^2) and mapped here (111.4×10^6 km^2) covers the 25 percent of Venus centered on the north pole. Processing and mosaicking of the radar data (Alexandrov et al., 1985; Bogomolov et al., 1985; Bockstein et al., 1988) were done by the Institute for Information Transmission Problems of the U.S.S.R. Academy of Sciences. We mapped the geology and structure at a reconnaissance level on the 27 1:5,000,000-scale quadrangles that resulted (U.S.S.R. Academy of Sciences, 1987, 1988); we then compiled this geology and structure on the 1:15,000,000-scale image mosaic prior to transferring it to an airbrush rendition of the mosaic (U.S. Geological Survey, 1989, sheet 2). (See NOTES ON BASE.)

Supplementary data used in mapping include a topographic dataset of combined Pioneer Venus and Venera altimetry data (E. Eliason, oral communication, 1990). This dataset was used to create a synthetic stereoimage (Batson et al., 1976) that was found to be useful for mapping (Kozak and Schaber, 1988). To a minor extent, Earth-based radar images were also used during mapping: Arecibo Observatory images covering the 20 percent of Venus' surface within 70 degrees of the sub-Earth point at inferior conjunction (roughly lat 0°N., long 325°) overlap the Venera images north of approximately lat 30°N. The Venera data are also overlapped by Goldstone images, but these have very low resolution (only 85 km; Goldstein and Rumsey, 1972).

Recently, Earth-based radar images of resolution comparable to those of Venera 15/16 have been obtained by Jurgens et al. (1988) and Campbell et al. (1989b) from the Goldstone and Arecibo radio telescopes, respectively. These images were not available at the time this map was prepared, but they will be valuable for geologic mapping (Campbell et al., 1989a, 1989c; Arvidson et al., 1990). Data from Magellan, scheduled for insertion into orbit around Venus in August 1990, will extend coverage to at least lat 70° S. and increase resolution by nearly an order of magnitude over that of existing images (Dallas, 1987; Saunders, 1988).

For the location of features mentioned in this report, see table 1. Features within the region of Venera coverage are also shown on the U.S. Geological Survey (1989) map.

UNIQUENESS OF VENUS

Venus is fundamentally similar to Earth: it is only 640 km (5 percent) smaller in diameter and has an observed density of 5.26 g/cm^3 (as compared with 5.52 for Earth). Major differences--extremely high surface temperature and lack of surface water--have significant effects on the physiography of the planet's surface. High temperatures reduce rock strength, reduce cooling rates, and prevent the existence of surface water. Lack of a significant hydrosphere, in turn, (1) precludes hydrothermal cooling effects (Lowell, 1975; Lister, 1977); (2) removes a strong chemical influence on the formation of both oceanic and continental crust (Campbell and Taylor, 1983; Cook, 1984; Koster van Groos, 1988); (3) precludes significant weathering and erosion (Langbein and Schumm, 1958; Judson, 1968; Costa and Baker, 1981); and (4) results in only one base level, which affects hypsography (Brass and Harrison, 1982; Phillips and Malin, 1983). Although rock strength increases with decreasing water content, the effect of high temperature dominates, and the net effect shortens relaxation time by orders of magnitude (Mueller, 1969; Solomon et al., 1982). As a rough guide, high-temperature creep begins when a material's homologous temperature, T_h (temperature, T, of the rock relative to its melting temperature, T_m), reaches 0.33-0.50 (Griggs et al., 1960; Misra and Murrell, 1965). Surface measurements by landers range from 446 to 470 °C (719 to 743 K); during descent, probes indicated air temperatures at the elevation of Maxwell Montes' summit to be near 377 °C (650 K; Seiff et al., 1980), giving an atmospheric temperature gradient of 8 °C/km (see also Kliore et al., 1986). Because dry basalt melts at around 1225 °C (1500 K) (Angenheister, 1982, p. 345), surfaces hotter than 500 K have the potential to creep over geologically short periods. Therefore, if Venus' surface layers have a basaltic composition (see TERRAIN INTERPRETED AS VOLCANIC, below), 100 percent of the surface is above 0.33 T_h and roughly 35 percent is above 0.5 T_h. A visible example of such creep may be Laima Tessera (Kozak and Schaber, 1986, 1987b; Sukhanov, 1986), the type area of Laima-type tessera (unit tl), which indeed exhibits flow-like structure (see also Barsukov et al., 1985). Venus' high surface temperature, the evidence in Venera 15/16 images, and theoretical models (Smrekar and Phillips, 1988) indicate that gravity-driven crustal deformation may have a significant effect on the appearance of Venus' surface.

Thermal-evolution considerations suggest that plate-like tectonism is presently occurring on Venus (Hsui and Toksoz, 1977; Meissner, 1983). The Veneras showed Venus' surface to be morphologically dichotomous: it has both elevated, highly fractured tesserae and low, smooth plains. Mountain belts and low ridges similar to those on lunar maria are seen between these two fundamental terrain types in some areas--clearly suggestive of plate-like tectonism. There is also good reason to expect that volcanism is currently active on Venus (Hsui and Toksoz, 1977; Walker et al., 1979; Meissner, 1983; Prinn, 1985; Wood and Francis, 1988). The most direct evidence is the Pioneer Venus ultraviolet spectrometer experiment data, which indicate a large influx of SO_2 into the atmosphere prior to the

Table 1. Names and locations of features mentioned in this report. Coordinates (in degrees) are those of the IAU Working Group for Planetary System Nomenclature (1986, work in progress). All latitudes are north except as noted. According to IAU convention, latitudes of northeast-trending features are given from south to north, those of northwest-trending features from west to east. Longitudes are given from west to east.

Name	Lat	Long
CHASMATA		
Dali	17-21 S	155-180
Daura	74-72	50-56
Ganis	19-10	188-200
Hecate	15-18	230-245
*Hina	63-66	18-22
Lasdona	72-66	30-40
Morana	71-67	24-25
**Parga	8-41 S	222-321
COLLES		
Akkruva	40-52	110-130
CORONAE		
Anahit	76-79	270-286
Bachue	72-75	250-270
*Nefertiti	34-37	47-51.5
*Nepret	53	7
*Neyterkob	48-51	203-206
Nightingale	61-66	126-135
*Ops	68.5	89
CRATERS		
Deken	47	288.5
Jadwiga	68.5	91
Volkova	74.5	243
Zhilova	66.5	125.5
DORSA		
Ahsonnutli	35-62	195-200
Bezlea	24-40	34-43
Lukelong	78-61	150-185
Pandrosos	52-70	205-215
Semuni	68-77	1-15
FOSSAE		
Hildr	40-47	160-161
*Manto	63-66	55-65
Sigrun	48-53	17-19
MONTES		
Freyja	73	335
Furki	36	236
Maxwell	65	4
Renpet	75-77	235-238
Tepev	29	45
Theia	25	281
PATERAE		
*Anning	66-66.5	57.5-58
*Bremer	67	64

Name	Lat	Long
Cleopatra	67	9
Colette	65	322
*Corday	62.5	40
*Pocahontas	65	49.5
Sacajawea	63	335
Trotula	41.5	19
Yaroslavna	39	21
PLANUM		
Lakshmi	75-60	320-360
REGIONES		
Bell	5-35	45-55
Beta	20-35	280-290
Eistla	10-25	350-50
Metis	2	245-255
Phoebe	10 N-20 S	275-300
Ulfrun	42 N-3 S	220-230
TERRAE		
Aphrodite	25 S-8 N	60-208
Ishtar	60-75	310-80
TESSERAE		
Ananke	46-56	125-140
Clotho	54-60	329-344
Fortuna	54-76	4-95
Kutue	37-42	105-110
Laima	58-45	31-59
Meshkenet	65-68	95-128
*Tellus	30-44	70-90
THOLUS		
Nertus	61.5	248

*Provisional name
**Name dropped

arrival of Pioneer Venus (Esposito, 1984). The question of whether tectonism is currently active is addressed below.

No clear evidence of modification of the surface by erosive agents, either at present or in the past, is seen at the resolution of the Venera images, although chemical and eolian weathering may possess a minor capacity for erosion (Volkov et al., 1986; Greeley et al., 1987b). Some evidence for this may be seen in Venera lander data (Florensky et al., 1977; Garvin et al., 1984). High surface temperatures, however, may actually cause eolian processes to retard weathering (Marshall et al., 1988). Given the high surface temperature, as well as the presence of slightly komatiitic rocks, there is also the possibility of erosion by high-temperature lava rivers (Huppert and Sparks, 1985). Such rivers may have formed the small, sinuous canyons in and around the basin between Maxwell and Freyja Montes.

PLATE 1
SURFACE AGE AND STRATIGRAPHIC CORRELATIONS

The moderate resolution of the available images prohibits discrimination of many age relations between terrain types; hence, individual areas of similar appearance are necessarily lumped into a single geomorphic-terrain type. The determination of impact-crater densities, a technique commonly used to constrain relative ages on other planetary bodies, is ineffectual for Venus because craters are so rare (density of 1.27×10^6 km^{-2} for craters larger than 10 km in diameter). With such inadequacies in resolution and crater density, it is difficult to make other than general statements about age relations, especially given the complexity of the terrain.

Based on crater densities, the average age of the northern quarter of Venus' surface has been estimated as (1) 1.0+/-0.5 Ga (Ivanov et al., 1986; Basilevsky et al., 1987); (2) 0.40 Ga (Shoemaker and Shoemaker, in press); and (3) 0.25+/-0.15 Ga (Schaber et al., 1987b), though this youngest age has been contested by Ivanov and Basilevsky (1987). To complicate matters, the occurrence of many craters within tectonic belts casts doubt on the postulated impact origin of some craters (Kozak and Schaber, 1987a; Schaber et al., 1987a). Greeley et al. (1987a) have pointed out that determination of the origin of small Venusian craters will require further knowledge of their setting. These uncertainties have led to conflicting interpretations for several craters, including Volkova, Zhilova, Deken, and Jadwiga: for examples, compare Basilevsky et al. (1987) with Sukhanov et al. (1989).

Another approach to placing a reasonable limit on surface age uses rheological arguments: extrapolating the heights of the surface backward in time (from present creep rates) strongly suggests that the greatest topographic highs and lows on Venus cannot be older than several hundred million years (Weertman, 1979; Solomon et al., 1982; Stephens et al., 1983). This approach does not allow discrimination of relative ages of units, however.

MAPPED GEOLOGIC/GEOMORPHIC UNITS

A variety of instruments on seven Venera landers provided data on the physical and chemical nature of the surface (Surkov and Barsukov, 1985). The Venera lander data suggest that basalts dominate the surface: high-K alkaline, tholeiitic, and calc-alkaline rocks were identified at the Venera 9, 10 and 14 landing sites; rocks at the Venera 13 and Vega 2 sites were found to be slightly komatiitic, whereas only the Venera 8 data suggest more acidic material, nepheline syenite (Surkov et al., 1986, 1987; Volkov et al., 1986, p. 148). Unfortunately, none of the landers touched down in tessera terrain, limiting our understanding of the different origins of the tesserae and the plains.

The plains consist of flood-type, presumably basaltic material with extremely large shields and many smaller shields and domical hills, whereas the tesserae generally lack volcanic constructs. The plains units are generally smooth and topographically featureless at Venera 15/16 resolution. However, the complex plains (unit pc) and parts of the intermediate plains (unit pi) contain more than 20,000 domical hills (unit dh), domical mesas (tholi, unit dm), and small shields (1-20 km in diameter), as well as large shields--all interpreted to be of volcanic origin. Most of the domical hills are clustered in a few dozen large fields (Slyuta et al., 1988). Akkruva Colles ("hills"), located between Ananke, Kutue, and Tellus Tesserae, for example, represent a major concentration of these fields of domical hills. The Akkruva Colles are interpreted to have been the result of thermal anomalies along a northwest-tending megarift described by Schaber and Kozak (1989b). This rift zone may be associated with global-scale crustal subsidence, and it has been suggested as being responsible for disruption of a "supertessera" that once existed in this region (Syluta, 1990).

The shields (unit s) may reach diameters of about 800 km and volumes of 4.4 X 10^5 km^3 (Schaber and Kozak, 1989a). In width, they rival Olympus Mons on Mars (600 km in diameter), though they are only a fraction as high--2 to 5 km. Many of these constructs are morphologically more similar to terrestrial swells (Le Bas, 1971) than shields: their height-to-width ratios are commonly >1:200 (Schaber and Kozak, 1989a), and some show medial rift-like structures. Two such structures--in the domed terrain of Bell Regio (unit bld) and in Metis Regio--appear to have developed on coronae (here, unit co_1), having either formed concurrently with or later partly buried ridges of the coronae. If so, these domed features may represent a late stage in the evolution of coronae.

Probable volcanic products of the type described above are notably absent from the tessera cores. However, flood-type deposits are pervasive along the perimeters of tesserae and are mapped as tesserae-mantling plains (unit pt). The dearth of volcanism on the tesserae is presumed to reflect a thicker lithosphere beneath them, due in part to stacking of thrust sheets (Basilevsky, 1986; Kozak and Schaber, 1987b, 1989; Vorder Bruegge and Head, 1989; Head, 1990; plate 2). The increase in probable volcanism away from tessera cores has been concentrated where extension and downfaulting appear to have played a part, as along the northwest and southwest sides of Laima Tessera; these areas have been rifted by fractures associated with Sigrun Fossae (on the northwest) and Bezlea Dorsa (on the southwest). Landforms mapped as craters (paterae) (unit cp) are commonly aligned along these rifts; for example, Corday, Pocahontas, Anning, and Bremer Paterae occur along the Sigrun Fossae-Manto Fossae rift trend between lat 61° and 68° N. and long 40° and 65°. Isolated constructs inferred to be volcanic that lie directly over tesserae are rare, but two domical hills were found in Daura Chasma in northern Fortuna Tessera. Although the two overlapping highland shields marked by Colette and Sacajawea Paterae are exceptions to the general rule that shields occur only in the low plains, these two shields do occur on the smooth plains of Lakshmi Planum (unit psl). The high elevation of the planum and the occurrence of islands of tesserae on it suggest that Lakshmi is a tessera that has been flooded by flows, dominantly from the two paterae. A genetic relation may exist between these anomalous highland shields and origin of the Lakshmi plateau, but such has not been established.

Craters (paterae) (unit cp) have various morphologies, but most paterae are shallow, irregular depressions less than 200 km in diameter. They have been interpreted to be calderas (Masursky et al., 1980) and ring complexes (Sukhanov, 1987b). The craters (paterae) are highly concentrated within the global disruption zones (Kozak and Schaber, 1989) in lineated terrain, type 1 (unit l_1) and ridge belts, type 1 (unit rb_1). Some paterae such as Yaroslavna have an unusual appearance, similar to that of nested saucers; they may result from flexure of a very thin lithosphere under volcanic overburden (Mueller and Saxena, 1977, p. 112; Sukhanov, 1987b).

Only one feature, Hildr Fossa, is seen that is similar to a lunar rille. Hildr is a few kilometers wide and more than 1,000 km long.

Coronae (units co_1 and co_2) are intriguing features that are common on Venus. They are domes, generally low (<2 km high) and broad (150 to 450 km across), comprising subcircular, concentric sets of low ridges that commonly bound a smooth, locally mottled inner floor. All observed coronae are between -1.0 and +2.0 km of the mean planetary radius (Edmunds et al., 1988). Many coronae straddle fracture zones (for example, Nightingale), or they are breached by flows from two points 180° apart (for example, Anahit), suggesting the presence of a fissure zone. Their smooth inner floors appear to be lava flow fields. Coronae have been interpreted as crustal swells that formed above mantle plumes; gravity then caused their brittle upper crustal layer to slide radially over a high-thermal-gradient decollement (Nikishin, 1986; Pronin and Stofan, in press; Stofan and Head, 1990). We think that concurrent and subsequent plume-related volcanism buried the concentric ridge belts at places, as at Bachue and Nefertiti Coronae, and that here volcanism continued, forming broad, low shields. The summits of these shields, in turn, are bisected by rifts, suggesting that the shields represent an intermediate step between coronae and the large rifted domes.

The presence of broad (1000 km wide), low (2-3 km high) uplands composed of dome terrain with axial chasmata was interpreted in Phoebe Regio and in Beta Regio (unit btd, between lat 30° and 40° N. and long 276° and 292°) from Earth-based radar images and altimetry data (Goldstein et al., 1976; Malin and Saunders, 1977; Campbell et al., 1984). These Earth-based data, acquired prior to receipt of the first spacecraft data, strongly suggest a relation between the apparent volcanism and the rifting, as well as a relatively young age for these regions. Pioneer Venus data defined the extent of these uplands, and the Venera images confirmed that they are highly fractured and suggested that they are at least partly volcanic in origin. The combined data have allowed a fairly detailed determination of the nature of Beta Regio (Stofan et al., 1989). Pioneer Venus and Arecibo data suggest that, in addition to Beta and Phoebe, Ulfrun and Eistla Regiones and the highlands south of the map area cut by Ganis, Hecate, Dali, and Parga Chasmata are also similar to the domed uplands imaged by the Venera craft. Several of these areas have positive gravity anomalies, suggesting recent volcanism (Bowin et al., 1985; Basilevsky and Janle, 1987; Sjogren, 1988). Thus, an evolutionary progression may exist from plains to rifted plains, to coronae, to volcanic domes, to rifted domes.

TECTONISM

Evidence of tectonism on Venus was first suggested by images obtained in 1975 by Earth-based radio telescopes (Campbell et al., 1976), and it too has been confirmed by the Venera 15 and 16 images. They show Venus' surface to have the distinct morphologic dichotomy noted above: low plains (dominantly smooth plains, unit ps; and intermediate plains, unit pi) and high, structurally complex tesserae (dominantly Laima-type tesserae, unit tl; western and eastern Fortuna-type tesserae, units twf and tef, and undivided tesserae, unit tu). The mean elevations of these two terrains differ by about 1.7 km (Rodionova, 1984; Bindschadler and Head, 1989). As noted above, the lack of evidence of volcanism in the higher terrain may be due to a thicker lithosphere under the tesserae.

Along the boundaries between the plains and tesserae, marginal belts are common. Where tesserae adjoin low plains, these belts tend to be low (< 1.5 km high), and they are mapped as tessera-type marginal belts (unit mt). Where the belts are adjacent to the high plains of Lakshmi Planum, they are generally high (elevations as much as 11.5 km), and they are mapped as Lakshmi-type marginal belts (unit ml). The marginal belts have been interpreted as thrust belts at convergent margins (plate 2; Crumpler et al., 1986; Kozak and Schaber, 1987b, 1989; Vorder Bruegge and Head, 1989; Head, 1990). The highest marginal belt, Maxwell Montes, is at the boundary between two tessera terrains, suggesting maximum thickening there at the locus of collision of "continental" blocks.

The plains are interrupted by two major tectonically disrupted zones whose approximate axes are aligned roughly north-south at about long 30° (lineated terrain, type 1, unit l_1) and long 210° (mostly ridge belt, type 1, unit rb_1). The plains were apparently formed by flood lavas, and the disruption zones have been suggested to be crustal spreading zones (Kozak and Schaber, 1986, 1987a, 1987b; Sukhanov and Pronin, 1987, 1989). The marginal belts, as would be expected, appear to have been formed by crustal convergence, and the tesserae both by accretion of convergent belts and by upper crustal delamination and subsequent gravity deformation. The lack of volcanic arcs may be due to shallow subduction, lack of water, or both, as suggested by Nur and Ben-Avraham (1982) for the volcanic gaps along the South American trench.

The concentrations of tesserae from long 290° eastward to long 140° suggest that they might have once formed one large tessera before the development of several tectonic troughs, such as those containing Sigrun and Manto Fossae and Ops Corona. Several small fragments of tesserae are found south of western and central Ishtar Terra and immediately south of Laima Tessera. The fragments south of Laima strongly suggest one way in which the large blocks may have disintegrated into isolated ones: fault-bounded troughs developed near the edges of the tesserae and were concurrently flooded by lavas. In contrast to this mostly vertical tectonism, horizontal tectonism has also been suggested as a means of dispersal of tesserae; examples are (1) crustal spreading (as at the ridge belt zone near long 210°; Kozak and Schaber, 1987b, 1989; Sukhanov and Pronin, 1987, 1989); (2) gravity spreading (as at Laima Tessera; Kozak and Schaber, 1986; Sukhanov, 1986); and (3) microplate-like drift (Clotho Tessera; Kozak, 1989). Evidence of crustal extension outside the area of Venera coverage has also been suggested for the equatorial rift system, which includes Aphrodite Terra (Schaber, 1982; Head and Crumpler, 1987; Crumpler and Head, 1988). Sukhanov and Pronin (1989) proposed models for lithospheric spreading on Venus based on a lithosphere more plastic than Earth's. Overlapping spreading centers on Earth (Macdonald et al., 1988) may be rough analogs to this type of spreading.

Sukhanov and Pronin (1989) also pointed out that structures similar to terrestrial transform features are not associated with the ridge belts. They noted, however, some faults (with probable displacements of as much as 150 km) oblique to ridge belts, and they suggested that total extension may be on the order of 2500 km. Another area of possible transcurrent offset was described by Kozak (1989): a complex linear zone (lat 60° N., long 345° to lat 53° N., long 10°) that is associated with the abrupt, linear terminus of southwestern Fortuna Tessera.

Gravity data acquired by Doppler tracking of the Pioneer Venus Orbiter indicate that topography is highly correlative with gravity potential and that compensation must occur, but further interpretations from the gravity data are unfortunately nonunique (Ananda et al., 1988). Slight gravity anomalies do appear related to the tectonic zones seen in the Venera images and have been interpreted as indicating current activity (Sjogren, 1988).

The geomorphologic and other observations discussed above suggest that horizontal tectonism has strongly controlled the morphology of the surface, yet the style of tectonism has only vague similarities to Earth's.

PLATE 2
STRUCTURE

The structure map shows major tectonic features as well as minor structural patterns interpreted primarily from analysis of the Venera 15/16 data. In regions of extremely complex tectonic fabric, such as types 1 and 2 of the lineated terrain (units l_1 and l_2), only major or representative structures have been mapped to avoid exceeding a desired level of map detail. Thrust faults shown are considered to be "interpretative" pending analysis of the forthcoming Magellan data.

Only those craters of suspected impact origin that are larger than 44 km in diameter are shown on plate 1, whereas all suspected impact structures are indicated on plate 2. However, a strong concentration of craters and paterae, all with central peaks, near Trotula Patera and the complex tectonic fabric surrounding Cleopatra Patera (Kozak and Schaber, 1987a; Schaber et al., 1987a) raise the suspicion that several of the crater-form features may not be of impact origin.

Because of the sensitivity of radar backscatter to aspect angle, look direction will strongly bias the representation of structural trends (MacDonald et al., 1969; also see Koopmans, 1983). This factor should be kept in mind when analyzing the structure map.

DESCRIPTION OF MAP UNITS
(PLATE 1)

[Surface compositional information within the map area is limited mostly to K, U, and Th abundances at the Venera 9 landing site (lat 31.7° N., long 290.8°). Analysis of these data indicates a composition similar to terrestrial basalt-like rocks (Surkov and Barsukov, 1985). A basalt-like composition is inferred for the plains, shield, and domical hills units, based primarily on their general morphologic characteristics and on analogs from studies of comparative planetology. An asterisk by unit symbol indicates a single occurrence. No correlation chart of map units is given because of the uncertainty of their relative ages. Elevations are distances to the center of mass of Venus, derived from a merged version of the Pioneer-Venus and Venera 15/16 altimetry datasets (E. Eliason, oral commun., 1990)]

PLAINS UNITS

ps SMOOTH PLAINS--Nearly featureless at Venera 15/16 resolution. Generally at low elevations (mean is 6051.20 km; standard deviation (SD) is 0.54 km). Slopes 0.0° to 0.15° at 100-km slope length. Type area: 55° N., 202°, between Ahsonnutli and Pandrosos Dorsa. Interpretation: Lava flood deposits similar to maria on Moon and Tharsis plains on Mars *psl **SMOOTH PLAINS OF LAKSHMI PLANUM**--Same as smooth plains, but mean elevation 6054.94 km (SD = 0.57 km). Type area: Lakshmi Planum. Interpretation: Lava flood deposits, probably covering tessera

pi **INTERMEDIATE PLAINS**--Intermediate between smooth and complex plains; some textural or subtle albedo variations; varied quantities of domical hills, minor ridges, fractures, and flows of differing roughness. Mean elevation 6051.35 km (SD = 0.67 km). Type area: none, due to the many possible expressions. Interpretation: Lava flood deposits

pc **COMPLEX PLAINS**-- Relief generally low and albedo complex; common small ridges, broad domes, lobate features, domical hills, troughs and circular depressions. Mean elevation 6051.13 km (SD = 0.50 km). Slopes 0.15° to 0.30° at 100-km slope length. Type area: 51° N., 78°. Interpretation: Lava flood deposits. Vents, fractures, and grabens may be present; circular depressions may be calderas

pm **MOTTLED PLAINS**-- Exhibit lobate forms locally elongated downslope; high or mottled albedo. Mean elevation 6051.84 km (SD = 0.54 km). Type area: 77° N., 332°. Interpretation: Lobes are individually identifiable lava flow fields

pt **TESSERAE-MANTLING PLAINS**--Smooth, intermediate, or mottled plains that occur dominantly on tesserae but also on marginal belts and ridge belts. Mean elevation 6053.01 km (SD = 1.60 km). Type area: 53° N., 36°. Interpretation: Lava plains that have locally buried tesserae, marginal belts, or ridge belts

TESSERAE

A tessera (from the Latin word for tile) is an elevated landform with distinct boundaries and subparallel, sharp ridges and valleys. Some segments that are too small or modified to be otherwise identified as to type are classified based on proximity to a recognizable unit.

tl **LAIMA-TYPE TESSERA**--Dominated by parallel grabens averaging 20 km in width, as much as 1,600 km long, and 100 to 300 km apart. Grabens are smooth floored and a few hundred meters deep; they generally trend downslope in southeastern Laima Tessera. Grabens are mimicked by a parallel fracture trend. Secondary fracture set occurs perpendicular to grabens and their parallel fractures; these secondary fractures have more uniform spacing of about 10 km. Unit is similar in appearance to young oceanic crust. Mean elevation 6052.54 km (SD = 0.70 km). Type area: Laima Tessera. Interpretation: Gravity-deformed, thin, detached upper crustal layer

twf **WESTERN FORTUNA-TYPE TESSERA**--Characterized by subparallel ridges and valleys with a wavelength of about 20 km, similar in appearance and scale to those of Basin and Range Province of southwestern U.S. No significant cross-cutting structure as in Laima type. Mean elevation 6054.99 km (SD = 1.52 km). Type area: 65° N., 15° (Fortuna Tessera west of Morana Chasma). Interpretation: Result of thin-skin delamination of upper crustal layers above large thermal disturbance or underthrust blocks

*tef **EASTERN FORTUNA-TYPE TESSERA**--Contains subparallel ridges and valleys 10 to a few hundred kilometers long, which occur in sets whose trends are continuous over domains 200 to 800 km long, commonly ending abruptly at border of other domains with different trends. Trends in individual domains may be superposed. Mean elevation 6053.52 km (SD = 0.76 km). Type area: 68° N., 45° (Fortuna Tessera east of Morana Chasma). Interpretation: Similar to western Fortuna type, but overprinted by one or more additional tectonic events; possibly composed of accreted fragments of western Fortuna type and ridge belt type 1 (unit rb_1)

*th **HINA-TYPE TESSERA**--Distinguished by low, subparallel ridges (6- to 12-km spacing) that tend to occur in parallel sets (about 6-km spacing). Trend of northern part of unit nearly parallel to Hina Chasma at Hina, but trend of eastern part swings to southeast, radial from point near north terminus of Hina. Lower surface relief than tessera units described above. Mean elevation 6055.32 km (SD = 0.67 km). Type area: 60° N., 20° (east of Hina Chasma). Interpretation: May have originated as fissure flows from along Hina Chasma (paired ridges may be flow levees); subsequently tectonically deformed

*tg **GROOVED TESSERA**--Found only on Lakshmi Planum. Contains two obliquely oriented groove sets; otherwise, relief is low. Embayed by plains material. Mean elevation 6055.51 km (SD = 0.13 km). Type area: 66° N., 338°. Interpretation: Uncertain, but possibly ignimbrite-like deposits related to Sacajawea Patera

tf **INTENSELY FRACTURED TESSERA**--Of high elevation, contiguous to other tesserae; high density of strongly linear, parallel fractures. Fracture trends parallel Sigrun/Manto Fossae and Lasdona Chasma rift axes (Kozak and Schaber, 1989). Mean elevation 6053.43 km (SD = 1.01 km). Type area: 62° N., 40° (near Corday Patera). Interpretation: Fractures are faults along axis and margins of rift zone that crosses highland tesserae

tu **TESSERA, UNDIVIDED**-- Tessera fragment that cannot be further identified because of insufficient size, state of preservation, or proximity to a recognizable type. Mean elevation 6052.28 km (SD = 1.00 km).

CORONAE

co_1 **CORONA, TYPE 1**--Large (100-400 km in diameter) circular or oblong set of concentric ridges (<1 km relief); most coronae have central low area of smooth plains. Mean elevation 6051.98 km (SD = 0.59 km). Type area:

Anahit Corona. Interpretation: Gravity-flow folds on crustal swell induced by mantle convection

co_2 **CORONA, TYPE 2**--Smooth, annular ridge enclosing smooth-floored depression. Ridges generally less than 300 km in diameter and 500 m high. Mean elevation 6051.38 km (SD = 0.47 km). Type area: Neyterkob Corona. Interpretation: Origin unknown; perhaps constructed by flows along rim fissures

DOMED TERRAINS

btd **DOMED TERRAIN OF BETA REGIO**-- Forms high areas of Beta Regio characterized by deep grabens and troughs trending both normal and parallel to slope. Summit of dome at 27° N., 282° exceeds 5 km in elevation, and Theia Mons (not shown) exceeds 6 km (U.S. Geological Survey, 1989, sheet 1). Mean elevation of unit within map area 6053.40 km (SD = 1.06 km). Type area: 37° N., 285°. Interpretation: Result of large-scale domical uplift of basaltic plains and associated extension and magmatism (Stofan et al., 1989); troughs are medial rifts and splay fractures

bld **DOMED TERRAIN OF BELL REGIO**--Elevated, smooth plains in Bell Regio that gradually rise to 1.5-km elevation near regio center at 31° N., 51° and at Nefertiti Corona. Mean elevation within map area 6051.91 km (SD = 0.68 km). Type area: 29° N., 48° (Bell Regio). Interpretation: Gently sloping plains formed by lavas from Nefertiti Corona, Tepev Mons, and other, unidentified sources; some elevation due to domical uplift

MARGINAL BELTS

ml **LAKSHMI-TYPE MARGINAL BELT**--Characterized by continuous, subparallel to parallel ridges whose crests are sharp to rounded; ridge axes generally concordant with those of adjacent tesserae. Includes elevated mountain belts (as much as 11.5 km high) and adjacent foothills surrounding Lakshmi Planum. Mean elevation 6056.57 km (SD = 2.28 km). Regional slopes 0.5° to >2.0° at 100-km slope length. Type area: 65° N., 3° (Maxwell Montes). Interpretation: Stacked imbricate thrust sheets resulting from collisions between Lakshmi Planum and surrounding tesserae, locally accompanied by underthrusting of adjacent plains material (as at northern Freyja Montes)

mt **TESSERA-TYPE MARGINAL BELT**-- Contains distinct bands of low ridges parallel to tessera boundaries; ridge belts generally <2 km higher than plains, extend <200 km from tessera edges. Ridge axes generally discordant with those of adjacent tesserae. Mean elevation 6052.57 km (SD = 1.15 km). Type area: 77° N., 10° (Semuni Dorsa). Interpretation: Fold or thrust belts resulting from convergence of plains units with thicker tesserae, though some may be ridge belts accreted to tesserae (as in northeastern Fortuna Tessera)

LINEATED AND FRACTURED TERRAINS

l_1 **LINEATED TERRAIN, TYPE 1**--Characterized by anastomosing, commonly subparallel or radiating swarms of bright lineaments about 5 km wide in zones of mottled albedo as much as several thousand kilometers long and several hundred kilometers wide. Relief of few lineaments is distinguishable. Lineaments commonly associated with grabens and intermediate-sized (50 to 200 km in diameter) paterae (unit cp; "arachnoids" of Barsukov et al., 1986, who called this unit "cobweb terrain"). Mean elevation 6051.03 km (SD = 0.56 km). Type area: 43° N., 23°. Interpretation: Terrain resulting from complex, horizontal, crustal extensional stresses and vertical stresses associated with magmatism. Lineaments are fractures, scarps, or fissure vents whose brightness results from small-scale roughness

l_2 **LINEATED TERRAIN, TYPE 2**--Distinguished by swarms of sublinear, subparallel, diffuse lineaments 5 to 10 km wide and 10 to 40 km apart characterized by high albedo. Lineaments exhibit little distinguishable relief. Mean elevation 6051.36 km (SD = 0.67 km). Type area: 50° N., 91°. Interpretation: Same as type 1, but result of more uniform horizontal stress field

f **FRACTURED TERRAIN**--Contains abundant linear troughs, mostly parallel. Small areas between Maxwell and Frejya Montes exhibit sinuous depressions. Lower fracture density than intensely fractured tessera (unit tf). Mean elevation 6052.65 km (SD = 1.51 km). Type area: 50° N., 18° (Sigrun Fossae). Interpretation: Linear troughs are grabens; sinuous depressions may be rille-like lava channels

LANDFORMS INTERPRETED AS VOLCANIC

s **SHIELD**--Roughly symmetric construct >100 km in diameter; commonly has identifiable summit crater or fissures and linear high albedo zones radial to summit. Mean elevation 6052.65 km (SD = 1.24 km). Type area: 76° N., 236° (Renpet Mons). Interpretation: Volcanic shield with common flank fissures and radial lava flows

dh **DOMICAL HILL OR HILL FIELD**--Individual dome-like hills <50 km in diameter and <2 km high. May form fields as large as 100 km in diameter or linear zones as large as 5,000 by 1,000 km. Mean elevation 6051.55 km (SD = 0.47 km). Individual edifices in fields generally average <10 km in diameter and <1 km in height; summit craters common. Density of hills in fields averages about 200 per 10^6 km^2 but, locally, can exceed several thousand per 10^6 km^2 (Slyuta et al., 1988). Type hill: Furki Mons. Type field: Akkruva Colles. Interpretation: Small composite volcano or shield; summit craters are volcanic vents

dm **DOMICAL MESA (THOLUS)**--Pancake-shaped, low dome, commonly about 100 km in diameter. Mean elevation 6051.45 km (SD = 0.52 km). Type area: 61.5° N., 247.5° (Nertus Tholus). Interpretation: Extrusion of lava of intermediate viscosity

cp CRATER (PATERA)--Relatively smooth floored depression with distinctly rougher walls and rim. Floor may be dark to mottled. Mean elevation 6051.94 km (SD = 1.16 km). No type area due to wide variation in morphologic expression. Interpretation: Caldera or volcano-tectonic depression

RIDGE TERRAINS

r **RIDGE**--Linear to sinuous, as much as 700 km long but may be shorter where partly buried by plains material; length of discontinuous ridge segments may total 1200 km; width <25 km. Mean elevation 6051.24 km (SD = 0.66 km). Type area: 38° N., 137°. Interpretation: Thin layer of plains material folded into narrow anticline

rb_1 **RIDGE BELT, TYPE 1**--Belt of 10 to 20 parallel ridges as much as 1 km high and spaced fairly uniformly, about 10 km apart. Belts are 100 to 200 km wide and thousands of kilometers long. They commonly bifurcate and rejoin at craters (paterae) (unit cp) or type 2 coronae (unit co_2). Mean elevation 6051.02 km (SD = 0.70 km). Type area: 55° N., 207° (Pandrosos Dorsa). Interpretation: May indicate divergent margin (Sukhanov and Pronin, 1987; Kozak and Schaber, 1989). Evidence for compression (Sukhanov, 1987a; Frank and Head, 1988) probably indicates that extensional stresses are limited to narrow axis of spreading

rb_2 **RIDGE BELT, TYPE 2**--Consists of subparallel 5-to 20-km- wide ridges with rounded crests within linear depression <3,000 km long, <200 km wide, and 0.5 to 1.5 km deep. Mean elevation 6051.38 km (SD = 0.54 km). Type area: 73° N., 180° (Lukelong Dorsa). Interpretation: Thin layers of plains material folded into synclinorium over underthrust substrate

rs **RIDGE SWARM**--Parallel ridges of noticeable relief 20 to 100 km apart, separated by smooth plains. Length-to-width ratios of ridges 1:30 to 1:>100. Mean elevation 6051.46 km (SD = 0.58 km). Type area: 38° N., 102°. Interpretation: Ridges possibly formed by eruptions along fissure vents

rc **RIDGE COMPLEX**--Contains parallel ridges having noticeable, commonly varied relief and wide range of length-to-width ratios (1:2 to 1:40); ridges about 10 km apart. Mean elevation 6051.85 km (SD = 0.59 km). Type area: 52.5° N., 14°, east of Nepret Corona. Interpretation: Fractured; probable lateral offset parallel to ridges; extrusion along fractures formed ridges

MISCELLANEOUS UNITS

h **HILLY TERRAIN**--Morphologically complex; consists of linear hills about 40 km long and domical hills, all of which produce a mottled albedo; cut by fractures and grabens. Mean elevation 6052.74 km (SD = 0.82 km). Type area: 64.5° N., 101°, south of Meshkenet Tessera. Interpretation: Volcanic and tectonic terrain with too much detail to allow delineation of individual features at scale of map

c **SUSPECTED IMPACT CRATER >44 KM IN DIAMETER**--Circular to subcircular, sharp-rimmed depression, commonly with central peak or ring. Rim deposits of many craters distinguishable. Mean elevation 6051.12 km (SD = 0.65 km). Interpretation: Crater of suspected impact origin (Basilevsky et al., 1987), although some mapped craters may be of volcanic or volcano-tectonic origin.

ce **EJECTA OF SUSPECTED IMPACT CRATER**--Smooth to undulatory, plains-forming deposits extending radially from craters. Albedo commonly higher than surrounding areas. Mean elevation 6051.48 km (SD = 0.45 km). Interpretation: Originally deposited as shock-melted and partly fluidized mass

MAP SYMBOLS

PLATE 1

Unit boundary, approximately located

Venera 9 landing site

PLATE 2

Fault--Dashed where approximately located; bar and ball on downthrown side

Structures below shown by two line weights (heavier lines indicate major structures)

Thrust fault--Dashed where inferred; dotted where buried; sawteeth on upper plate

Scarp--Line at top of scarp; hachures point downslope

Depression

Graben

Ridge crest

Trough

Lineament--Dashed where approximately located; dotted where probable structure buried

Shear zone

Crater of probable impact origin--Impact origin of some craters questionable due to insufficient resolution of Venera 15/16 data

Venera 9 landing site

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NOTES ON BASE

Image information for this map was taken almost exclusively from Venera 15 and 16 synthetic aperture radar image mosaics provided by the U.S.S.R. (Rzhiga, 1987; Alexandrov et al., 1988). Ancillary data included Pioneer Venus radar altimetry (Pettengill, 1977; Pettengill et al., 1979), Venera 15 and 16 radar altimetry (Kotelnikov et al., 1984, 1985) and Earth-based radar images provided by the Arecibo Observatory (Campbell and Burns, 1980; Stofan et al., 1987).

ADOPTED FIGURE

The figure of Venus used for computing the map projection is a sphere with a mean radius of 6051.0 km (Kotelnikov et al., 1985).

PROJECTION

The Polar Stereographic projection is used for this map, with a scale of 1:15,000,000 at lat 40°N. and 1:18,261,561 at lat 90°N. Due to the retrograde rotation of Venus, longitudes increase from west to east in accordance with usage of the International Astronomical Union (IAU, 1983).

CONTROL

Planimetric control is taken from the radar-image mosaic provided by the U.S.S.R. that is based on the tracked position of the spacecraft (Akim et al., 1986; Tyuflin et al., 1989). According to current IAU convention, the 0° meridian passes through the center of a craterlike feature, Eve (lat 32°S.), located within Alpha Regio, a feature of the southern hemisphere that is outside the area shown on this map (Masursky et al., 1980). No simple statement for accuracy can be given, but discrepencies as great as 10 km (0.1°) are likely to exist (Alexandrov et al., 1985; Tyuflin et al., 1989).

NOMENCLATURE

For clarity, place names are omitted from this map. They are shown on the U.S. Geological Survey map (1989).

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