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Geologic Map of the Nemesis Tesserae Quadrangle (V–13), Venus

By Mikhail A. Ivanov and James W. Head, III

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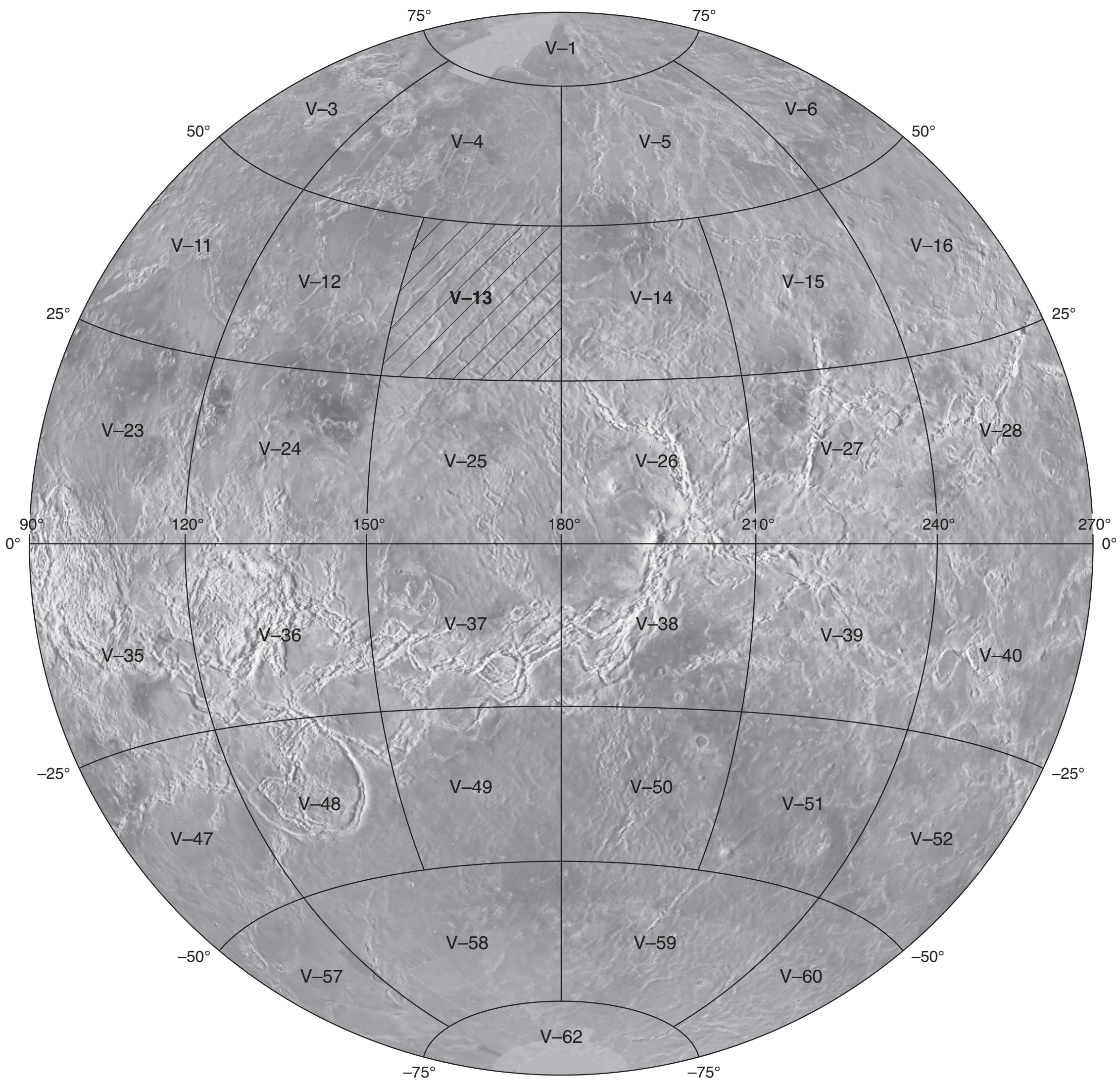

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THE MAGELLAN MISSION

The Magellan spacecraft orbited Venus from August 10, 1990, until it plunged into the Venusian atmosphere on October 12, 1994. Magellan Mission objectives included (1) improving the knowledge of the geological processes, surface properties, and geologic history of Venus by analysis of surface radar characteristics, topography, and morphology and (2) improving the knowledge of the geophysics of Venus by analysis of Venusian gravity.

The Magellan spacecraft carried a 12.6-cm radar system to map the surface of Venus. The transmitter and receiver systems were used to collect three data sets: (1) synthetic aperture radar (SAR) images of the surface, (2) passive microwave thermal emission observations, and (3) measurements of the backscattered power at small angles of incidence, which were processed to yield altimetric data. Radar imaging and altimetric and radiometric mapping of the Venusian surface was accomplished in mission cycles 1, 2, and 3 from September 1990 until September 1992. Ninety-eight percent of the surface was mapped with radar resolution on the order of 120 m. The SAR observations were projected to a 75-m nominal horizontal resolution, and these full-resolution data compose the image base used in geologic mapping. The primary polarization mode was horizontal-transmit, horizontal-receive (HH), but additional data for selected areas were collected for the vertical polarization sense. Incidence angles varied between about 20° and 45°.

High-resolution Doppler tracking of the spacecraft took place from September 1992 through October 1994 (mission cycles 4, 5, 6). Some 950 orbits of high-resolution gravity observations were obtained between September 1992 and May 1993 while Magellan was in an elliptical orbit with a periapsis near 175 km and an apoapsis near 8,000 km. An additional 1,500 orbits were obtained following orbit-circularization in mid-1993. These data exist as a 75° by 75° harmonic field.

Radar backscatter power is determined by (1) the morphology of the surface at a broad range of scales and (2) the intrinsic reflectivity, or dielectric constant, of the material. Topography at scales of several meters and larger can produce quasi-specular echoes, with the strength of the return greatest when the local surface is perpendicular to the incident beam. This type of scattering is most important at very small angles of incidence, since natural surfaces generally have few large tilted facets at high angles. The exception is in areas of steep slopes, such as ridges or rift zones, where favorably tilted terrain can produce very bright signatures in the radar image. For most other areas, diffuse echoes from roughness at scales comparable to the radar wavelength are responsible for variations in the SAR return. In either case, the echo strength is also modulated by the reflectivity of the surface material. The density of the upper few wavelengths of the surface can have a significant effect. Low-density layers such as crater ejecta or volcanic ash can absorb the incident energy and produce a lower observed echo. On Venus, there also exists a rapid increase in reflectivity at a certain critical elevation, above which high-dielectric minerals or coatings are thought to be present. This leads to very bright SAR echoes from virtually all areas above that critical elevation.

The measurements of passive thermal emission from Venus, though of much lower spatial resolution than the SAR data, are more sensitive to changes in the dielectric constant of the surface than to roughness. As such, they can be used to augment studies of the surface and to discriminate between roughness and reflectivity effects. Observations of the near-nadir backscatter power, collected using a separate smaller antenna on the spacecraft, were modeled using the Hagfors expression for echoes from gently undulating surfaces to yield estimates of planetary radius, Fresnel reflectivity, and root-mean-square (rms) slope. The topographic data produced by this technique have horizontal footprint sizes of about 10 km near periapsis and a vertical resolution on the order of 100 m. The Fresnel reflectivity data provide a comparison to the emissivity maps, and the rms slope parameter is an indicator of the surface tilts, which contribute to the quasi-specular scattering component.

MAGELLAN SAR AND RELATED DATA

The SAR instrument flown on the Magellan spacecraft (12.6 cm, S-band) provided the image data used in our mapping and interpretation. SAR images are a record of the echo (radar energy returned to the antenna), which is influenced by surface composition, slope, and wavelength-scale surface roughness. Viewing and illumination geometry also will influence the appearance of surface features in SAR images. Guidelines for geologic mapping using Magellan SAR images and detailed background to aid in their interpretation can be found in Elachi (1987), Saunders and others (1992), Ford and Pettengill (1992), Tyler and others (1992), and Tanaka (1994). In the area of the Nemesis Tesserae quadrangle, incidence angles are such that backscatter is dominated by variations in surface roughness at wavelength scales. Rough surfaces appear relatively bright, whereas smooth surfaces appear relatively dark. Variations also occur depending on the orientation of features relative to the incident radiation (illumination direction), with features normal to the illumination direction being more prominent than those oriented parallel to it. Full-resolution images have a pixel size of 75 m; C1-MIDRs contain the SAR data displayed at about 225 m/pixel. Altimetry data and stereo images were of extreme importance in establishing geologic and stratigraphic relations between units. Also essential in the analysis of the geology of the surface are data obtained by

Magellan on the emissivity (passive thermal radiation), reflectivity (surface electrical properties), and rms slope (distribution of radar wavelength scale slopes). Aspects of these measurements were used in unit characterization and interpretation; background on the characteristics of these data and their interpretation can be found in Saunders and others (1992), Ford and Pettengill (1992), Tyler and others (1992), Tanaka (1994), and Campbell (1995).

NEMESIS TESSERAE QUADRANGLE

The Nemesis Tesserae quadrangle (V–13) is in the northern hemisphere of Venus and extends from lat 25° to 50° N. and from long 150° to 180° E. (fig. 1*A*,*B*). It covers the area between Atalanta Planitia to the north, Vellamo Planitia to the west, and Llorona Planitia to the southwest. Nemesis Tesserae consists of an elongated centralized deformed lowland flooded by volcanic deposits and surrounded by the Vedma Dorsa deformation belt to the west (Kryuchkov, 1990; Frank and Head, 1990) and Nemesis and Athena Tesserae to the east (fig. 1*A*). In contrast to more equidimensional lowlands (basins) such as Atalanta and Lavinia Planitiae, the area of the Nemesis Tesserae quadrangle represents the class of elongated lowland areas on Venus confined between elevated regions (fig. 1*B*). The Nemesis Tesserae quadrangle is an important region for the analysis of processes of basin formation and volcanic flooding.

Before the Magellan mission, the region of Nemesis Tesserae quadrangle was known on the basis of Pioneer-Venus altimetry to be a lowland area (Masursky and others, 1980; Pettengill and others, 1980). Venera-15/16 radar images showed that the interior of the area was populated with complex patterns of deformational features in the form of belts of ridges and volcanic plains, and several regions along the margins were seen to be the sources of large radar-bright areas interpreted to be lava flows (Barsukov and others, 1986; Sukhanov and others, 1989). Early Magellan results showed that the ridge belts are composed of complex deformational structures predominantly of contractional origin (Squyres and others, 1992; Solomon and others, 1992) and that the complex lava flows along the margins emanated from corona-like sources outside of the map area at the northern and southern edges of Nemesis Tesserae quadrangle (Head and others, 1992). The global analysis of the distribution of volcanic features revealed that the interior of Nemesis Tesserae is an area deficient in the distribution of large volcanic centers and coronae and coronalike features (Head and others, 1992; Crumpler and others, 1993; Crumpler and Aubele, 2000), but small shields are abundant in the map area.

The gravity and geoid data show that the lowland is characterized by a –35-mGal gravity anomaly and a –40-50-m geoid anomaly, centered on the eastern portion of the quadrangle (Konopliv and Sjogren, 1994; Konopliv and others, 1999). The area of Nemesis Tesserae quadrangle is the southern continuation of the large Atalanta Planitia, which is characterized by a circular shape, low topography, and a –35-mGal gravity anomaly and a –55-m geoid anomaly. These features of Atalanta Planitia have been cited as evidence for the region being the site of large-scale mantle downwelling (Phillips and others, 1991; Bindschadler and others, 1992b). Thus, this region could represent a laboratory for the study of the evolution of a flanking zone of a lowland, the formation of associated tectonic features, and their relation to mantle processes. In an attempt to address these issues, several questions appear to be very important: What units make up the surface of the map area? What is the sequence of these units and what events in the geologic history of the map area do they document? What is the history of large-scale topographic features in the area under study? What, if any, is the evidence for evolution of volcanic activities and styles of tectonic activities in this area? These questions and issues are the basis for our geologic mapping analysis.

In our analysis we focused on the geologic mapping of the Nemesis Tesserae quadrangle using traditional methods of geologic unit definition and characterization for the Earth (for example, North American Commission on Stratigraphic Nomenclature, 1983) and planets (for example, Wilhelms, 1990) appropriately modified for radar data (Tanaka, 1994). We defined units and mapped key relations using the full resolution Magellan SAR data (mosaicked full resolution basic image data records, C1-MIDRs , F-MIDRs, and F-Maps) and transferred these results to the base map compiled at a scale of 1:5,000,000. In addition to the SAR image data, we incorporated into our analyses digital versions of Magellan altimetry, emissivity, Fresnel reflectivity, and roughness data (rms slope). The background for our unit definition and characterization is described in Tanaka (1994), Basilevsky and Head (1995a,b; 2000), Basilevsky and others (1997), and Ivanov and Head (1998), although other approaches to the mapping technique also exist (Guest and Stofan, 1999; Hansen, 2000).

GENERAL GEOLOGY

Several different geologic processes influenced the Nemesis Tesserae region and combined to form its geologic record. Owing to the lack of water and efficient erosion processes (Arvidson and others, 1992), volcanism is the dominant process of crustal formation on Venus (Head and others, 1992) and it produced the observed geologic units in this map area. Tectonic activity modified some of these basic crustal materials (for example, Solomon and others, 1992; Squyres and others, 1992) in a variety of modes (extension, contraction, and shear), and in places deformation is so extensive, as in the case of tessera terrain, that the deformational features become part of the definition of the material unit (see also Tanaka, 1994; Scott and Tanaka, 1986; Campbell and Campbell, 2002; Hansen and DeShon, 2002). Impact cratering also has locally influenced regions in the quadrangle but, in general, has not been an influential process over the quadrangle as a whole (fig. 2). Aeolian processes require a source of sediment to produce deposits and, thus, are concentrated around impact craters and localized around tectonic fractures and scarps (for example, Greeley and others, 1992).

At the north edge of the Nemesis Tesserae quadrangle the southern portion of large Bolotnitsa Fluctus is visible, and an intermediate volcanic edifice, Fedsova Patera, is situated in the northeast corner of the map area (Crumpler and others, 1993; Crumpler and Aubele, 2000); small shield volcanoes less than about 15 km in diameter (Guest and others, 1992; Aubele and Slyuta, 1990) are common in association with deformation belts but relatively rarely occur within the vast extent of regional plains. There are two meanings of the term "plains" (Mescherikov, 1968). In a strict morphological sense, plains define morphologically uniform surfaces with relatively small differences in relief. In a broader sense, plains are counterparts of highlands and define vast flat terrains. In the strict sense, the term "plains" is simply a descriptor of a type of the surface and does not bear an interpretative meaning. At the higher level of interpretation is the term "volcanic plains" that implies knowledge or inference of the nature of material that makes up the plains. In the case of Venus, however, the materials that form plains are most likely of volcanic origin. In the broader sense, the term "plains" usually describes large physiographic provinces (for example, North American Plain, Russian Plain). Thus, the same term can define two different classes of morphologic/physiographic features. Although the specific meaning of the term "plains" is usually clear from the context, possible conflict of the term usage can appear. Fortunately, in the planetary nomenclature the physiographic and physiographic/topographic meanings of the term "plains" are strictly defined. A vast plainlike and more or less homogeneous physiographic province is called "planitia" if it is at middle to low elevations (for example, Atalanta Planitia or Isidis Planitia) or "planum" if it is elevated (for example, Lakshmi Planum or Hesperia Planum). Following this rule, we use the term "plains" in the nongenetic, morphological sense throughout this publication. On the basis of their specific morphologic and physical property characteristics, we define various different plains units (see Description of Map Units). For example, lobate plains differ from shield plains and so on. The small shields are low in elevation, commonly have a summit pit, do not appear to have distinct associated flows, and are commonly embayed by subsequent regional plains deposits. Concentrations of small shield volcanoes occur predominantly in the eastern part of the quadrangle. Several steep-sided domes (Pavri and others, 1992; Ivanov and Head, 1999) are found in the Nemesis Tesserae quadrangle. There are no officially recognized coronae (Stofan and others, 1997) within the quadrangle, but a coronalike feature is visible at about lat 43° N., long 177° E. (fig. 2). Distinct lava flows enter the quadrangle from its north edge (fig. 1*A*; Bolotnitsa Fluctus shows no association with a distinct source) and at the southwest corner (fig. 1*A*; northern portion of Llorona Planitia, its surface of lava flows associated with Ituana Corona, which is outside of the map area); an intermediate volcano, Fedsova Patera (fig. 1*A*) is also surrounded by distinct lava flows. Most of the quadrangle contains relatively homogeneous wrinkle ridged plains material interpreted to be of volcanic origin and modified by narrow and low wrinkle ridges to varying, but usually low, degrees. The source vents for these plains are not well known. Some of these plains display radar backscatter variations and apparent flow fronts that permit stratigraphic distinctions among subunits. The composition of these volcanic plains is not known from data in this quadrangle, although Venera 9 and 10 (northeast and southeast slope of Beta Regio, respectively) and Vega 2 (Rusalka Planitia) lander geochemical analyses of sites in similar terrains suggest compositions similar to terrestrial tholeiitic basalt (Basilevsky and others, 1992).

The most important volcanic feature within the quadrangle is Baltis Vallis (fig. 1*A*), the longest (about 7,000 km long) channel on Venus (Baker and others, 1992, 1997; Basilevsky and Head, 1996). Baltis Vallis runs through the central portion of the quadrangle, and its channel lies in the middle part of a broad elongated lowland (fig. 1*B*) between the elevated area of Vedma Dorsa to the west and a high-standing region composed of Nemesis Tesserae and Athena Tessera to the east. Regardless of the nature of material that formed the channel of Baltis Vallis, it must have formed during a geologically short time interval and at a relatively even topographic gradient (Komatsu and Baker, 1994). Such characteristics make Baltis Vallis important both as a regional stratigraphic marker (Basilevsky and Head, 1996) and as an indicator of the post-channel tectonic deformation (Komatsu and Baker, 1994).

Tectonic features in the Nemesis Tesserae quadrangle include a few individual narrow (less than about 1–2 km) grabens, 150–200 km in length, that indicate extensional deformation and are concentrated in the southeast corner of the map area. The grabens, mapped as sharp grooves in this portion of the map area, form a compact zone hundreds of kilometers wide that resembles rifts and rift-like zones elsewhere on Venus. Wrinkle ridges are widespread throughout the plains; their typical length is several tens of kilometers and their width is a few kilometers. Ridges with larger amplitude and longer wavelength, called arch and ridge belts, are concentrated preferentially in Vedma Dorsa in the western part of the quadrangle (Stewart and Head, 2000). Wrinkle ridges, arches, and ridge belts indicate contractional deformation (anticlines and thrust faults). There is no evidence for significant shear deformation within the quadrangle. In some places, several styles of tectonic activity operated together or in sequence to produce terrain more heavily deformed than typical wrinkle ridged plains. The most extreme examples are in Nemesis Tesserae and Athena Tessera in the east-central part of the quadrangle. Tessera terrain within the map area and elsewhere on Venus is heavily deformed by both contractional and extensional structures that usually have multiple sets of features intersecting at high angles (for example, Barsukov and others, 1986; Bindschadler and others, 1992a; Ivanov and Head, 1996; Hansen and Willis, 1996). Typically, the deformation in tessera is so closely spaced that it becomes a major part of the unit definition.

Seven impact craters are mapped in the quadrangle (fig. 1; table 1). The craters range in diameter from 2 km to 20.4 km for crater Anaxandra (Schaber and others, 1998). Seven splotches (surface markings and deposits interpreted to be formed from airblasts from projectiles traversing the atmosphere; for example, Schaber and others, 1992; Ivanov and others, 1992) were detected in the quadrangle (fig. 2). Surface deposits emplaced during the cratering event (both outflow deposits and remnants of dark haloes; Schaber and others, 1992; Phillips and others, 1992; Campbell and others, 1992; Schultz, 1992) are noted and are particularly associated with craters Datsolalee and Udyaka in the eastern part of the quadrangle. There are no areas within the quadrangle apparently covered with fragmental surface materials that have been redistributed by aeolian processes.

STRATIGRAPHY

On the basis of an analysis of the global size-frequency distribution of impact craters, a crater retention age of about 800 Ma (McKinnon and others, 1997), about 500 Ma (Schaber and others, 1992; Phillips and others, 1992), or about 300 Ma (Strom and others, 1994) have been proposed for the present surface of Venus. The crater areal distribution cannot be distinguished from a spatially random population, which, together with the small total number of craters, means that crater size-frequency distributions cannot be used to date stratigraphic units for an area the size of the Nemesis Tesserae quadrangle (Hauck and others, 1998; Campbell, 1999). Therefore, attention must be focused on the definition of geologic units and structures and the analysis of crosscutting, embayment, and superposition relations among structures and units to establish the regional geologic history.

We mapped material geologic units independently of tectonic structures, which are secondary features disturbing a material substrate. Nevertheless, in many cases tectonic features are such a pervasive part of the morphology of the terrain that it becomes part of the definition of a unit at the map scale. For example, our tessera unit is similar to Aureole members 1–4 of the Olympus Mons Formation, which are defined on the basis of tectonic structure ("...corrugated, cut by numerous faults that formed scarps and deep troughs and grabens...", Scott and Tanaka, 1986). Our plains unit with wrinkle ridges is analogous to Member 1 of the Arcadia Formation on Mars ("Low-lying plains; mare-type (wrinkle) ridges common"). In other cases, the approach depends on scale and density of structures. For example, where the structures are more discrete and separated, we map them separately and not as a specific unit; whereas in other cases, where they are very dense and tend to obscure the underlying terrain, we choose to map them as a unit. These approaches are used by the vast majority of investigators mapping Venus (see review in Basilevsky and Head, 2000), although differences of opinion exist (for example, DeShon and others, 2000; Ivanov and Head, 2001a,b; Rosenberg and McGill, 2001; Bridges and McGill, 2002; Campbell and Campbell, 2002; Hansen and DeShon, 2002). Here we summarize the stratigraphic units and structures and their relations.

Tessera material (fig. 3, 4). The unit interpreted to be stratigraphically oldest in the quadrangle is tessera material (unit t), which is embayed by most of the other units within the map area. Tessera material is radar bright, consists of at least two sets of intersecting ridges and grooves, and is a result of tectonic deformation of some precursor terrain (Barsukov and others, 1986; Basilevsky and others, 1986; Bindschadler and Head, 1991; Sukhanov, 1992; sometimes referred to as complex ridged terrain, Solomon and others, 1992). Arches, ridges, grooves, and grabens are tectonic features, so structure is an essential component of the tessera terrain and a key aspect of the unit definition. Globally, tessera occupies about 8 percent of the surface of Venus (Ivanov and Head, 1996) and occurs as large blocks and small islands standing above and embayed by adjacent plains. These types of occurrence are mirrored in this quadrangle, where the relatively small tessera blocks (500 x 300 km and up to 1,000 x 400 km across), Nemesis Tesserae and Athena Tessera, are exposed.

Densely lineated plains material (fig. 3, 5, 6). The stratigraphically oldest plains unit is densely lineated plains material (unit pdl), which is characterized by relatively flat surfaces on a regional scale and by swarms of parallel and subparallel lineaments (resolved as fractures if they are wide enough) having typical spacing of less than 1 km. Although the unmodified precursor terrain for the densely lineated plains material is not observed, the regional flatness suggests that it was volcanic plains material. Although fractures are structural elements, they are such a pervasive part of the morphology of this terrain that it becomes a key aspect of the definition of the unit, as in several of the Mars examples cited above. Densely lineated plains predominantly occur in areas surrounding Nemesis and Athena Tesserae, and small patches of the plains occur in the eastern and southern part of the quadrangle, often in close association with shield plains. In places where the plains are in contact with tessera there is evidence for abrupt truncation of the tessera structures by the plains (fig. 6), which suggests that densely lineated plains postdate tessera.

Ridged and grooved plains material (fig. 3, 7, 8). Following the emplacement and deformation of densely lineated plains material, a plains material of relatively high radar albedo was emplaced. This plains material embays occurrences of previous units such as tessera and densely lineated plains and, in turn, is broadly embayed by subsequent plains material. The most striking morphologic characteristic of the unit is that its occurrences typically host sets of relatively broad (5–10 km wide) ridges tens of kilometers long that are absent in the previous and subsequent units.

Although the ridges are structural elements, they are important features that help to define and map extensions of the unit. For instance, there is not much doubt that wrinkle ridges deform materials that form regional wrinkle ridged plains. Hypothetically, a wrinkle ridge or collection of them would represent kipukas of wrinkle ridged plains if younger lavas would flood the rest of the unit. If this hypothetical situation is mapped at a scale sufficient to outline individual exposures (wrinkle ridges) of a material largely covered by younger material then the true structural elements, wrinkle ridges, should be included in the material unit. The scale of our mapping is mostly sufficient to map exposures of a material unit represented on the surface by arches and ridge belts. This is unit prg and it is a material unit, although it is exposed by deformation and represented in many cases by structures.

The ridged and grooved plains material in the Nemesis Tesserae quadrangle is arranged in linear outcrops or belts such as Vedma Dorsa, which is 50–200 km wide and up to 1,500 km long. Vedma Dorsa is largely equivalent to the ridge belts of Squyres and others (1992). Elongated occurrences of ridged and grooved plains material are oriented predominantly north-northeast–south-southwest in the western and central part of the Nemesis Tesserae quadrangle, but at the southern edge of the quadrangle they are oriented north-northwest–south-southeast. In the western part of the quadrangle occurrences of the unit probably represent the southernmost extension of the ridge-belt concentration in the Pandrosos Dorsa area (northeast of the map area; Rosenberg, 1995). In places, ridged and grooved plains are in contact with densely lineated plains (fig. 8). In these localities material of unit prg clearly embay fragments of densely lineated plains implying a younger relative age of ridged and grooved plains.

Shield plains material (fig. 3, 9, 10). Following the emplacement of ridged and grooved plains material, shield plains material (unit psh) of intermediate radar albedo was emplaced. This unit is characterized by abundant small shield-shaped features ranging from a few kilometers in diameter up to about 10–20 km, commonly with summit pits. Although small clusters of shields were recognized earlier planetwide (Head and others, 1992), they were thought to be localized occurrences possibly related to individual sources such as hot spots. Later work in Vellamo Planitia (Aubele, 1994, 1995) recognized that many of these occurrences represented a stratigraphic unit in this region, and subsequently this unit has been recognized in many areas on the planet (Basilevsky and Head, 1995b; Basilevsky and others, 1997; Ivanov and Head, 1998), including this quadrangle. Shields characterizing this unit occur in clusters, giving the unit a locally hilly texture, and as isolated outcrops in relatively smooth plains. The shields are interpreted to be of volcanic origin (Aubele and Slyuta, 1990; Guest and others, 1992) and are likely to be the sources of some adjacent smooth plains material. In the Nemesis Tesserae quadrangle, however, there is no clear evidence for specific flow units associated with the small edifices of shield plains material (fig. 9). The unit is widely distributed in the quadrangle but occurs predominantly in its southeastern and east-central parts around Nemesis and Athena Tesserae. A few occurrences of shield plains material are associated with ridge belts of Vedma Dorsa in the west half of the quadrangle. There are almost no concentrations of shield plains material in the central and south-central portions of the quadrangle, where the plains appear to be buried by younger plains units. Some isolated shields (for example, at about lat 43° N., long 177° E.) occur where subsequent plains units embay shield plains and form kipukas (flooding the bases of the shields and leaving the tops exposed). The radar brightness of the two units commonly is different, which permits an estimate to be made of the thickness (about 100–200 m) of the margins of the embaying unit using existing information on the height of the shields (Guest and others, 1992; Kreslavsky and Head, 1999). This conclusion is based on a detailed study of the morphometry of small shields in a number of regions on Venus. In all areas studied, the results are consistent and provide about the same value of the thickness of wrinkle ridged plains (pwr_1). Thus, we infer that the thickness of wrinkle ridged plains within the map area is comparable to the thickness estimates elsewhere on Venus. At contacts with ridged and grooved plains material, there is evidence of embayment of this unit by material of shield plains (fig. 10), which means that shield plains are younger.

Wrinkle ridged plains material (fig. 3, 11, 12). After the emplacement of these earlier plains units, the most widespread plains unit in the quadrangle, wrinkle ridged plains material, was emplaced. This unit is composed of morphologically smooth, homogeneous plains material of intermediate-low to intermediate-high radar albedo complicated by narrow linear to anastomosing wrinkle ridges (a structural element) in subparallel to parallel lines or intersecting networks. This unit is analogous to the ridged unit of the plateau sequence on Mars (Scott and Tanaka, 1986), which is a plains unit defined by "long, linear to sinuous mare-type (wrinkle) ridges." In the map area, the wrinkle ridges typically are less than 1 km wide and as much as tens to hundreds of kilometers long. In some areas they may be smaller, whereas in others they are larger. Their trend often varies locally even within one site. The unit is interpreted to be regional plains material of volcanic origin that was subsequently deformed by wrinkle ridges (for example, Stewart and Head, 2000). Volcanic edifices and sources of the plains are not obvious although some small shield-shaped features are seen that appear to be kipukas of shield plains material (unit psh). Wrinkle ridged plains material is subdivided into two units (fig. 11). The lower unit (unit pwr_1) generally has a relatively low radar albedo but can be mottled locally. The upper unit (unit pwr_2) generally has a relatively high radar albedo and lobate boundaries. In the northern and southern portions of the quadrangle, material of unit pwr_2 penetrates into areas occupied by unit pwr_1 using local lows such as small-scale fractures and lava channels. For instance, in the north, material of Bolotnitsa Fluctus (unit pwr_2) penetrates into the channel of Baltis Vallis (fig. 11). This is strong evidence that unit pwr_1 is older than unit pwr_2. Together these two units form more than 70–75 percent of the surface of the quadrangle and occur predominantly in low-lying regions between elongated highs composed of pre-existing units and ridge belts (for example, between Vedma Dorsa and Nemesis/Athena Tesserae area in the central and southern parts of the quadrangle). Unit pwr_1 is the most widespread of the two units, and unit pwr_2 forms less than about 10 percent of the combined area of both units. Unit pwr_2 occurs sporadically throughout the quadrangle. At contacts with shields plains material, there is evidence for embayment of unit psh by material of unit pwr_1 (fig. 9, 10, 12), meaning that regional wrinkle ridged plains mostly postdate shield plains.

Smooth plains material (fig. 3, 13). The youngest plains units in the stratigraphic sequence are characterized by morphologically smooth surfaces commonly unmodified by wrinkle ridges or other structural elements. Smooth plains have uniform albedo that varies from low to high in different localities. In the Nemesis Tesserae quadrangle, smooth plains occur predominantly in small patches. In the northeastern part of the quadrangle, smooth plains occur inside Fedsova Patera.

Impact crater material (fig. 3, 14). Impact craters and related deposits are observed in several places in the quadrangle (fig. 2). Their locations are noted by symbols and they are subdivided into undivided crater material (unit c) of various diameters with proximal textured and outflow deposits (unit cf). Several craters are characterized by surrounding radar dark material that partly to wholly obscures the underlying terrain. Dark haloes apparently related to four impact craters within the quadrangle (Anaxandra, Datsolalee, Udyaka, and unnamed crater at lat 35.8° N., long 164.5° E.) are shown in fig. 2. All impact craters and related materials are superposed on wrinkle ridged plains. We did not observe impact craters in the quadrangle that may be embayed by lava flows of any stratigraphic position. There are also no craters in the Nemesis Tesserae quadrangle that are cut by tectonic features.

STRUCTURES

A variety of tectonic features is observed and mapped in the quadrangle. Long linear fractures and some paired scarps interpreted to be grabens are seen in the southeast corner of the quadrangle. They are 50–200 km long, are oriented northwest–southeast, and cut material units of shield plains and the lower unit of wrinkle ridged plains material. The grabens in this part of the map area appear to form a compact zone of extensional structures resembling a rift zone that is much more prominent elsewhere on Venus. The general orientation of the rift-like zone in the southeast corner of the quadrangle continued the trend of a major branch of rifts that run north-northwest from Atla Regio (V–26) and may represent the northernmost extension of the rift.

Several types and scales of features of contractional origin are observed within the quadrangle. Wrinkle ridges are seen throughout the quadrangle (fig. 2) and are so important in the broad plains that they, in part, define and characterize wrinkle ridged plains material. These features were mapped in a representative sense by individual wrinkle ridge symbols to show dominating trends, but smaller and more chaotically oriented ridges are sometimes abundant in between the most prominent trends. There are several trends of wrinkle ridges in the quadrangle. In the southeast quarter of the map area, wrinkle ridges trend northwest parallel to the strike of structures within small fragments of ridge belts (prg). In the southwestern part of the quadrangle, wrinkle ridges trend west-northwest almost orthogonal to the orientation of ridges and arches of the Vedma Dorsa ridge belt. In the northern part of the map area wrinkle ridges trend predominantly east-west, also at high angles to the strike of the structures of ridge belts.

Ridged and grooved plains material (unit prg) is dominated by ridges and arches (figs. 2, 7, 8). Ridged and grooved plains material forms predominantly north-northeast- and northeast-trending bands or belts that are largely equivalent to the ridge belts of Squyres and others (1992). Basilevsky and Head (1995a,b; ridge belts, RB) described a structure, which was a belt consisting of a cluster of densely spaced ridges 5–10 km wide and a few tens of kilometers long; this unit was often transitional to ridged and grooved plains material (unit prg). Although we did not map ridge belts in this area, the belts of ridged and grooved plains are closely related. For instance, a significant portion of a large occurrence of unit prg within Vedma Dorsa (between about lat 35° N. and lat 42° N.) represents a typical ridge belt.

Several sets of both contractional and extensional structures are seen in tessera (unit t). In the east-central portion of the map area, the tessera ridges are oriented predominantly west-northwest, roughly parallel to elongation of individual tessera fragments of Nemesis and Athena Tesserae. Extensional structures such as fractures and grabens are typically oriented at high angles to the ridges. In places, additional sets of structures are seen in tessera material and these apparently are related to the deformation in younger units, for example, in densely lineated plains material.

GEOLOGIC HISTORY

The Nemesis Tesserae area represents the southern flanking zone of the large, relatively equidimensional lowland of Atalanta Planitia and is an important region for analysis of processes of lowland formation and volcanic flooding. Major questions include the following: What is the sequence of events in the formation and evolution of large-scale lowlands on Venus? What are the characteristics of the marginal areas surrounding these basins? When did the flanking zone of the Atalanta Planitia basin form, and is there any evidence that either the basin or its surroundings represent a stage in the evolution of other terrain types, such as tessera? How do the units in Nemesis Tesserae quadrangle compare with each other, and what information do they provide concerning models for Venus global stratigraphy and tectonic history? Here we discuss the stratigraphic positions of units, their temporal correlation, and the implied geologic history of the region. We also examine the sequence of tectonic deformation and its interpretation as well as the evolution of volcanic styles. We conclude with an assessment of the geologic history of Nemesis Tesserae area in relation to models for the global evolution of Venus.

The stratigraphically oldest unit in the map area is tessera (fig. 4), a relatively high-standing (fig. 1*A*,*B*) complexly deformed unit, the largest outcrops of which are exposed in Nemesis and Athena Tesserae. Smaller massifs of tessera within the map area are represented by unnamed tessera patches in close proximity to the Nemesis and Athena Tesserae in the central and eastern parts of the map area (fig. 1*A*). Tessera is consistently embayed by a variety of younger plains materials (units pdl, prg, psh, pwr_1, and pwr_2) of apparent volcanic origin. The principal massif of Nemesis Tesserae shows numerous parallel and subparallel narrow ridges a few kilometers across cut by narrow and shallow grabens and fractures that are mostly orthogonal to the ridges. The same basic sets of structures occur within Athena Tessera. Consistent with observations made on regional (Bindschadler and others, 1992a) and global scales (Ivanov and Head, 1996), tessera material in Nemesis and Athena Tesserae was formed from some precursor material that was initially deformed by shortening, folding, and probably shear, which produced more highly deformed terrain than seen in any subsequent units on Venus, and associated extensional deformation (cut by fractures and grabens of various types) to produce the generally orthogonal structural fabric typical of much of the tessera planetwide. Other smaller outcrops are exposed as kipukas in the quadrangle, and on the basis of this distribution and the global distribution of similar small outliers, tessera terrain is thought to exist extensively in the subsurface beneath younger plains units. No direct evidence exists in the map area for the duration of the formation of the characteristic structural pattern of tessera, but global crater studies (Ivanov and Basilevsky, 1993; Gilmore and others, 1997) suggest that it was of relatively short duration (for example, tens of millions of years).

Marginal to the tessera terrain and embaying it is plains material that has been densely fractured (unit pdl) and in some cases has a structural fabric orientation similar to the latest phase of deformation in tessera. Where occurrences of densely lineated plains material are in contact with tessera fragments, fractures of the plains appear to continue the structural trend of some of the sets of structures in tessera. The deformation patterns in densely lineated plains material are very dense and unidirectional (fig. 5, 6) in contrast to the orthogonal patterns of the tessera, and the role of extension and perhaps shear in the formation of the structural pattern of unit pdl is evident. This unit is interpreted to be volcanic plains material that embayed early tessera material and that was deformed by the latest phases of tessera deformation. There is no clear evidence of a transition between densely lineated plains material and tessera material in the map area. Densely lineated plains material makes up a small percentage of the surface outcrop but is widespread in the map area and occurs within elevated areas in the western and eastern parts of the quadrangle, suggesting more extensive presence in the subsurface. Following the emplacement and deformation of densely lineated plains material (unit pdl), another plains material (fig. 7) was emplaced (ridged and grooved plains material, unit prg). Although little evidence exists for sources, the smooth surface texture of the background material of the unit strongly suggests that it is of volcanic origin. The most important features of ridged and grooved plains material are ridges, usually curvilinear arches 5–10 km wide, which are pervasive and comparable to lunar contractional mare arches (Frank and Head, 1990). The presence of the ridges means that, after emplacement as lava plains, the unit underwent contractional deformation. Occasional grooves (extensional structures) cut the ridges and indicate a late and local tension regime.

Occurrences of the unit apparently make up a very broad arc extending generally in the north-south direction along the west edge of the map area. The unit occurs as broad arches (as much as 75–200 km across) striking generally north-south in the western part of the map area and northwest-southeast in the southern and eastern parts. The parallelism of the strike of the tectonic features and broad arches of this unit suggests that the deformation that produced the tectonic features is also similar to that which produced the arches. Thus, the period during which this unit was formed was characterized by emplacement of widespread volcanic plains and their subsequent deformation into broad arches with distinctive ridges. On the basis of its present topographic configuration, this unit and its deformation appear to have produced the second-order topography of extensive lowland in the west half of the Nemesis Tesserae quadrangle, that is, broad segmentation into local low regions defined by linear and curvilinear arches of ridged and grooved plains standing several hundred meters above the surrounding terrain.

Following emplacement and deformation of ridged and grooved plains material, another distinctly different plains unit (shield plains material, unit psh) was emplaced in many parts of the map area and is now preserved as extensive occurrences preferentially in the eastern and southeastern parts of the map area around Nemesis and Athena Tesserae and as patches in relatively high areas elsewhere in the quadrangle. The abundant shield volcanoes and intershield plains (fig. 9) that are characteristic of this unit are noticeably different from the volcanic style of both ridged and grooved plains material and subsequent wrinkle ridged plains material. The extent of these vents indicates widespread local and shallow magma sources during the emplacement of shield plains. The close association of this unit with densely lineated plains material suggests that the widespread shields may be related to extensional deformation at least locally. The shield plains material (unit psh) embays ridged and grooved plains material. The symmetry of the shields suggests that they were emplaced on a relatively flat surface. The lack of extensive development of deformational features demonstrates that regional deformation had further waned in intensity. Small edifices of shield plains are typically embayed by wrinkle ridged plains material. This strongly suggests that shield plains material is mostly an older unit.

Subsequent to the emplacement of shield plains material and its continued downwarping and tilting, the style of volcanism changed. Instead of abundant small shield volcanoes, broad plains (fig. 11), now regionally deformed by wrinkle ridges (unit pwr_1), were emplaced from sources that are now largely unknown. The presence of sinuous channels (a large segment of Baltis Vallis and the channel of Hoku-ao Vallis) occur in the central and southern parts of the map area (Baker and others, 1992, 1997; Komatsu and Baker, 1994; Basilevsky and Head, 1996), and the wide areal extent of this unit suggests emplacement in high-effusion-rate eruptions from a few sources in distinct contrast to the widespread and abundant small shield volcanoes just preceding this phase.

At least several occurrences of unit pwr_2 in the northeast corner of the quadrangle are adjacent to later smooth plains material (unit ps) at Fedsova Patera. Bolotnitsa Fluctus, which is an extensive area of unit pwr_2, is apparently associated with Holde Corona (lat 53.5° N., long 155° E.) within the area of Atalanta Planitia (V–4) quadrangle. Another extensive occurrence of this unit is in the southern part of the map area and is associated with a large volcanolike source (Ituana Corona, lat 19.5° N., long 154° E.) outside the south margin of the Nemesis Tesserae quadrangle. This type of association of unit pwr_2 suggests that regional deposition of the lower unit of wrinkle ridged plains (material unit pwr_1) may have given way to deposits of the upper unit, which were associated with specific sources. Deposits of wrinkle ridged plains material cover well over one-half of the map area and are concentrated in the lowland areas between tessera outcrops and belts of ridged and grooved plains.

The presence of Baltis Vallis in the map area provides a somewhat unique opportunity to estimate the relative timing of the evolution of topography within the quadrangle. Baltis Vallis represents a regional stratigraphic marker and an indicator of topographic changes as well (Komatsu and Baker, 1994; Basilevsky and Head, 1996). The channel cuts the surface of unit pwr_1 and is embayed by the upper unit of the wrinkle ridged plains (unit pwr_2, fig. 11). Thus, the formation of the channel probably occurred no later than the final stages of the emplacement of the lower, most extensive unit of the wrinkle ridged plains (unit pwr_1). The channel of Baltis Vallis extends meridionally across the center of the map area and makes a broad loop around a highland to the east consisting of Nemesis and Athena Tesserae. The channel also is curved around ridge belts of Vedma Dorsa to the west. Such a position and regional planimetric shape of Baltis Vallis strongly suggest that the two principal highland areas in the quadrangle, Nemesis/Athena Tesserae and Vedma Dorsa (fig. 1*A*,*B*), existed as elevated regions before the formation of Baltis Vallis. Thus, most of the topography observed today was formed prior to the emplacement of the majority of wrinkle ridged plains material. The studies of the longitudinal topographic profile of Baltis Vallis (Baker and others, 1992, 1997; Komatsu and Baker, 1994; Stewart and Head, 1999, 2000) show, however, that since the formation of Baltis the topography within the Nemesis Tesserae quadrangle continued to evolve as documented in topographic changes along the channel of Baltis Vallis. These changes occurred at a local scale (a few hundred kilometers wavelength; a few hundred meters amplitude) compared with the regional scale of the largest basins and highlands (thousands of kilometers wavelength; a few kilometers amplitude).

The volcanic plains of units pwr_1 and pwr_2 were further deformed by the formation of wrinkle ridges subsequent to emplacement of the plains. Some wrinkle ridges in the southeastern part of the map area are oriented generally consistently with the tectonic fabric typical of ridged and grooved plains material. At the north end of the Vedma Dorsa ridge belt, broad topographic arches within wrinkle ridged plains are seen in both the synthetic stereo images and topographic profiles along Baltis Vallis (Komatsu and Baker, 1994; Stewart and Head, 1999, 2000). Thus, in these parts of the map area the deformation recorded in units prg, pwr_1, and pwr_2 appears to be consistent in structural trends, probably reflecting about the same orientation of major compressional stresses. In the majority of the territory, however, wrinkle ridges do not follow the strike of structures typical of unit prg (fig. 2) suggesting that the compressional stresses responsible for the formation of wrinkle ridges have been re-oriented and more chaotically distributed after emplacement of regional volcanic plains material. The clear diminishing of the contractional structures from the broad ridges and arches typical of unit prg to wrinkle ridges characterizing wrinkle ridged plains material implies a progressive change in shortening and deformation.

The volcanic plains of units pwr_1 and pwr_2 were further deformed by the formation of wrinkle ridges during and subsequent to their emplacement. Some wrinkle ridges in the southeastern part of the map area are oriented generally consistently with the tectonic fabric typical of ridged and grooved plains. In the majority of the territory, however, wrinkle ridges are almost orthogonal to the strike of structures typical of unit prg (fig. 2). Thus, the deformation recorded in units prg, pwr_1, and pwr_2 appears to be weakly consistent in structural trends and reflects both a decrease in the intensity of shortening and deformation and re-orientation of stress fields with time.

Small and relatively rare occurrences of smooth plains material (unit ps) were emplaced near the end of formation of wrinkle ridged plains material. Smooth plains material is similar to the underlying plains (unit pwr_1 and pwr_2) but is unmodified by wrinkle ridges (fig. 13) and was emplaced apparently randomly over the map area. Typically, smooth plains material occurs without association with distinct volcanic sources except for one case where the plains occur inside Fedsova Patera. There is no evidence for the deformation of smooth plains material by wrinkle ridges, which suggests that the plains are either very recent and as yet undeformed or that wrinkle ridge deformation as a general phenomena ceased by this time. Because smooth plains material occupies a small area and occurrences of unit ps are very small, none of these explanations can be ruled out based on the absence of deformation in smooth plains material. On the basis of the general decrease of contractional deformation scale as a function of time, we interpret the general absence of wrinkle ridges in smooth plains material to be the result of waning deformational forces. In summary, volcanism at the time of formation of smooth plains material apparently abruptly diminished and switched from the extensive floodlike plains units to small isolated flows playing a minor role in the history of volcanism within the Nemesis Tesserae quadrangle.

Of the seven impact craters seen in the map area (fig. 2), none is embayed by volcanic plains or individual flows; there are also no craters visibly cut by tectonic structures. Thus, all impact craters appear to be younger than the wrinkle ridged plains material. The lack of embayed craters could be interpreted to mean that the plains were probably emplaced in a relatively short period, although the small total number of craters makes this interpretation tentative.

In summary, the trends in the geologic history outlined here suggest that deformation decreased in intensity from an initially very high level associated with tessera formation to increasingly lower levels associated with deformation of densely lineated plains material, ridged and grooved plains material, wrinkle ridged plains material, and finally, to essentially no deformation of the latest flows of lobate plains. Trends in principle stress orientation suggest a relatively consistent post-tessera northeast-southwest principle compression axis orientation in the eastern part of the map area from early post-tessera through the emplacement of plains with wrinkle ridges. In the western and northern parts of the map area, re-orientation of the principal compression axis occurred after the emplacement of both units of wrinkle ridged plains and during the formation of wrinkle ridges. The large-scale topography of the Nemesis Tesserae quadrangle, which is the southern flanking zone of a large basin of Atalanta Planitia, initially formed at the time of deformation of ridged and grooved plains material (producing a series of smaller basins bounded by belts of unit prg). The readjustment of smaller-scale topography including some of the ridged and grooved plains structures continued after the emplacement of wrinkle ridged plains. Volcanism was initially widespread and partly coincident with tessera formation (for example, unit pdl), then became concentrated into widely distributed small individual sources (the small shields of unit psh), then changed style to vast flooding of the majority of the area, and lastly was concentrated over a few distinct volcanic sources. The volcanic activity in the Nemesis Tesserae quadrangle apparently waned after the tectonic episode of wrinkle ridge formation.

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Table 1. *Description of impact craters in the Nemesis Tesserae quadrangle, Venus (from Schaber and others, 1998)*

Name	Latitude (degrees)	Longitude (degrees)	Diameter (km)	Note
Anaxandra	44.2	162.3	20.4	Dark halo
unnamed	43.0	150.9	2.0	
Pasha	42.7	156.3	7.2	
Datsolalee	38.3	171.8	17.5	Dark halo, outflows
unnamed	35.8	164.5	3.5	Dark halo
Udyaka	30.9	172.9	7.7	Dark halo, outflows
Oshalche	29.7	155.5	8.3	