

yield estimates of planetary radius, Fresnel reflectivity, and root-mean-square (rms) slope. The topography data produced by this technique have horizontal footprint sizes of about 10 km near periapsis and a vertical resolution of approximately 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.

INTRODUCTION

others, 1986; Sukhanov and others, 1989). Venera 15 and 16 data also revealed that the

interior 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 interpreted as predominantly of contrac-

tional origin (Squyres and others, 1992; Solomon and others, 1992) and that the complex

lava flows along the margins emanated from coronae at western and southwestern edges of

of volcanic features revealed that the interior of Atalanta Planitia is somewhat deficient in

distinctive volcanic sources and coronalike features (Head and others, 1992; Crumpler and

Atalanta Planitia (Head and others, 1992). In addition, global analysis of the distribution

cm, S-band) provided the image data used in this 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. The Atalanta Planitia quadrangle (V–4) is in the northern hemisphere of Venus and Guidelines for geologic mapping using Magellan SAR images and detailed background to extends from 50° to 75° north latitude and from 120° to 180° east longitude. It covers the aid in their interpretation can be found in Elachi (1987), Saunders and others (1992), Ford central and western part of Atalanta Planitia and parts of its margins. Atalanta Planitia conand Pettengill (1992), Tyler and others (1992), and Tanaka (1994). In the area of the Atasists of a centralized deformed lowland flooded by volcanic deposits and surrounded by Nightingale and Earhart Coronae in Tethus Regio to the west (Pronin and Stofan, 1990; lanta Planitia quadrangle, incidence angles are such that backscatter is dominated by varia-Stofan and Head, 1990), Ananke Tessera (Ivanov and Head, 1996) and Vellamo Planitia tions in surface roughness at wavelength scales. Rough surfaces appear bright, whereas (Aubele, 1994, 1995) to the southwest, an extensive zone of ridge belt to the east (Kryuchsmooth surfaces appear dark. Variations also occur depending on the orientation of features relative to the incident radiation (illumination direction), with features normal to the kov, 1990; Frank and Head, 1990), Vellamo and Ganiki Planitiae to the south (Aubele, illumination direction being more prominent than those oriented parallel to it. Full-resolu-1994, 1995), Louhi Planitia to the northwest, and Lukelong Dorsa to the northeast (Kryuchkov, 1990; Frank and Head, 1990). In contrast to more elongate lowland areas on tion images have a pixel size of 75 m; C1-MIDR's contain the SAR data displayed at ~225 Venus, the Atalanta Planitia area is one of several large, somewhat equidimensional lowm/pixel. Altimetry data and stereo images were of extreme importance in establishing geolands (basins) and as such is an important region for the analysis of processes of basin forlogic 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 Before the Magellan mission, Atalanta Planitia was known on the basis of Pioneer radiation), reflectivity (surface electrical properties), and rms slope (distribution of radar Venus altimetry to be a lowland area (Pettengill and others, 1980); Venera 15 and 16 radar wavelength scale slopes). Aspects of these measurements were used in unit characterizaimages showed that it was surrounded by several coronae and coronalike features from the tion 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 west and by numerous ridge belts parallel to the basin margin to the east (Barsukov and

> others (1992), Tanaka (1994), and Campbell (1995). GENERAL GEOLOGY Several different geologic processes have influenced the Atalanta Planitia region and have combined to form its geologic record. Volcanism is the dominant process of crustal formation on Venus (Head and others, 1992) and production of 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, as has been done for Mars (see also Tanaka, 1994; Scott and Tanaka, 1986). Impact cratering also has locally influenced regions in the quadrangle, most notably in the area

MAGELLAN SAR AND RELATED DATA

(Guest and others, 1992). Wrinkle-Ridged Plains Material

The synthetic aperture radar (SAR) instrument flown on the Magellan spacecraft (12.6

sources of the plains are not obvious although some small shield-shaped features are seen and appear to be kipukas of shield plains material (unit psh). Wrinkle-ridged plains material is subdivided into two units. The lower unit (unit pwr₁) generally has a low radar albedo but can be mottled locally. The upper unit (unit pwr₂) generally has a high radar albedo and lobate boundaries. In the southern portion of the quadrangle, unit pwr₂ penetrates into areas occupied by unit pwr₁, using local lows such as small-scale fractures and lava channels. This relationship is strong evidence that unit pwr₁ is older than unit pwr₂. Together these two units form more than 60% of the surface of the quadrangle and occur predominantly in low-lying regions between linear highs composed of preexisting units and ridge belts (for example, Bolotnitsa Fluctus between Frigg Dorsa and Vedma Dorsa in the southern part of the quadrangle). Unit pwr₁ is more widespread than unit pwr₂, as unit pwr₂ forms less than about 30% of the combined area of the two units. Unit pwr₂ is concentrated mostly in the southern part of the quadrangle.

smooth plains material occurs predominantly in small patches along the northern, eastern, and southern margins and between Nightingale and Earhart Coronae. Lobate plains material occurs predominantly along the western and southwestern margins of the basin in the form of large flow deposits (for example, around Nightingale and Earhart Coronae) ema-

BELT MATERIAL Swarms of narrow grooves are concentrated in the western and southern parts of the quadrangle. In some cases, grooves are so closely spaced that they tend to obscure the terrain they are superposed on and their presence takes on a defining character to the terrain. These concentrations are characterized by numerous short and long curvilinear, subparallel and anastomosing lineaments that are commonly wide enough to be resolved as fractures and grabens. In detailed mapping at the FMAP scale, remnants of preexisting plains can be seen between these tectonic structures. Stratigraphic relationships of groove belt material and ridged and grooved plains material are unclear, because these units do not occur in contact with each other. Both units, however, pre-date shield plains material and apparently post-date densely lineated plains material. Thus, the belts of narrow grooves (made up of groove belt material, unit gb) and ridged and grooved plains material (unit prg) were formed after the deformation of densely lineated plains material (unit pdl) and before the emplacement of shield plains material (unit psh). Within the Atalanta Planitia quadrangle, groove belts form part of the annulae of Nightingale and Earhart Coronae and a starlike pattern of deformation in the core of Ciuacoatl Mons. At these coronae, structures of groove belts are mostly embayed by material of both shield plains and regional plains with wrinkle ridges. Orientations of grooves in groove belts are shown within the unit and generally trend parallel to the strike of the groove belts as a whole.

tured and outflow deposits—crater flow material (unit cf). Several craters are characterized by a surrounding of radar dark material that partly to wholly obscures the underlying terrain. Dark parabolas apparently related to three impact craters within the quadrangle (Monika, Ermolova, and Irinuca) are shown in fig. 1. We observed only one crater in the quadrangle that may be embayed by lava flows-Koidula (64.2° N., 139.6° E.; 76 km diameter)—of the lobate plains. No craters in the Atalanta Planitia quadrangle are cut by

Some surficial streaks and patches of apparently unconsolidated material that has been redistributed by eolian processes (for example, Greeley and others, 1992) are observed in the quadrangle but are not mapped as a specific unit. They are primarily in the northeastern corner of the quadrangle, where material from the crater Dickinson has been

STRUCTURES A variety of tectonic features is observed and mapped in the quadrangle. Long linear fractures and some paired and facing scarps interpreted to be grabens are seen in the eastern part of the quadrangle. They are 150-700 km long, oriented west-east, and spaced 50–150 km apart, cutting all stratigraphic units older than the upper unit of wrinkle-ridged plains material (unit pwr₂). In some cases, grabens are so closely spaced that they tend to obscure underlying terrain and their presence takes on a defining character to the terrain. Concentrations of grabens in groove belt material (unit gb) are distinguished from densely lineated plains material (unit pdl) by their beltlike form and the character of the fractures (more distinctly recognizable grabens in unit gb). Groove belt material appears to be distinctive stratigraphically. The structure of the belts crosscuts tessera material (unit t) in Nightingale Corona and, in turn, are mostly embayed by wrinkle-ridged plains material (unit pwr₁). Some of the structures of groove belts cut the surface of this latest unit. The individual fractures cutting many younger units and mapped as separate structures commonly are oriented in the same direction and may represent the waning stages of con-

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 this quadrangle. Tessera terrain 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, similar to the situation in the aureole members of the Olympus Mons Formation (Scott and Tanaka, 1986). Globally, tessera occupies about 8% 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 occurrences are mirrored in this quadrangle, where the northeastern portion of a large tessera block about 1,500 x 650 km across (Ananke Tessera) and the easternmost part of a smaller tessera massif (Meskhent Tessera) are exposed, and several small patches are seen elsewhere in

partially redistributed.

PLAINS MATERIALS Densely Lineated Plains Material The stratigraphically oldest plains unit is densely lineated plains material (unit pdl), which is characterized by somewhat 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 flatness suggests that it was plains. 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 Ananke and Meskhent Tesserae, and small patches of the plains occur in the central and northern part of the quadrangle, in places in close association with shield plains. Material of the plains, where it is in contact with tessera, embays tessera ridges and penetrates into grooves on the tessera surface. In turn, unit pdl appears to be embayed by

dominated by Monika and Dickinson craters, but in general has not been an influential

process over the quadrangle as a whole. Eolian processes require a source of sediment to

The eastern and northern flanks of two large volcanic edifices, Melia Mons and Jael

produce deposits, and thus deposits are concentrated around impact craters and localized

Mons (table 1; Head and others, 1992; Crumpler and others, 1993), are visible at the very

western edge and in the southwestern corner of the Atalanta Planitia quadrangle, respec-

tively. Small shield volcanoes less than about 15 km diameter (Guest and others, 1992;

Aubele and Slyuta, 1990; Crumpler and others, 1997) are common. 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. Although not

continuous, concentrations of small shield volcanoes occur over all parts of the quadran-

gle. No steep-sided domes (Pavri and others, 1992) have been found in the Atalanta Plani-

tia quadrangle. Coronae are not well developed or abundant in the lowlands of Atalanta

Planitia, but four coronae—Earhart, Nightingale, Mari, and Holde—and one coronalike

feature—Ciuacoatl Mons—are present (fig. 1) in the western and southern topographically

higher part of the quadrangle. The 370-km-diameter Earhart Corona (71.0° N., 136.0° E.)

and 560-km by 480-km Nightingale Corona (63.0° N., 130.0° E.) are exposed in the west-

ern part of the quadrangle and are two of several making up a cluster of coronae and coro-

nalike features in Tethus Regio outside the map area (Barsukov and others, 1986; Stofan

and Head, 1990; Stofan and others, 1992). Extensive lobate lava flows emanate from these

features and dominate the northwestern part of the quadrangle. Other lobate lava flows

enter the quadrangle from its southern edge, near one intermediate volcano and three small

coronae. Sources along ridge belts in the Pandrosos Dorsa area also produce lobate lava

flows, which enter the quadrangle from its eastern margin. Most of the quadrangle com-

prises relatively homogeneous plains interpreted to be of volcanic origin and modified by

tectonic structures 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

(northeastern and southeastern slope of Beta Regio, respectively) and Vega 2 (Rusalka

Planitia) lander geochemical analyses of sites in similar terrains suggest compositions

Tectonic features in the Atalanta Planitia quadrangle include individual narrow (less

Wrinkle ridges are widespread throughout the plains. These structures are sinuous and

than about 1-2 km) grabens hundreds of kilometers long, concentrations of parellel nar-

row grabens into belts, and some concentrations in such high density that the underlying

narrow (about a few kilometers wide). Their typical length is several tens of kilometers.

Ridges of longer wavelength are known as arches and ridge belts. Wrinkle ridges, arches,

No evidence for shear deformation exists within the quadrangle. In some places, sev-

eral tectonic styles have operated together or in sequence to produce terrain more heavily

deformed than typical regional plains. The interior and annulus of Nightingale Corona,

where fractures and grabens coexist, is an example of this. An extreme example is in

Ananke Tessera, in the southwest part of the quadrangle, where the deformation is so

Twenty-six impact craters are mapped in the quadrangle (fig. 1, table 2). The craters

intense that it becomes a major part of the unit definition (for example, Bindschadler and

range in diameter from 1.5 km to 100 km (Schaber and others, 1998). No splotches (sur-

face markings and deposits interpreted to be formed from air blasts from projectiles tra-

versing the atmosphere; for example, Schaber and others, 1992; Ivanov and others, 1992)

were detected in the quadrangle. Extended surface deposits emplaced during the cratering

event (both outflow deposits and remnants of dark haloes; Schaber and others, 1992; Phil-

lips and others, 1992; Campbell and others, 1992; Schultz, 1992) were noted and are par-

ticularly concentrated in the central part of the quadrangle around crater Ermolova (60.9

km diameter) and in the northwestern (around crater Monika, 25.5 km diameter), south-

western (at unnamed crater, 52.1° N., 123.2° E., 3.2 km diameter and Irinuca crater, 8.0

km in diameter), and southeastern (around crater Rampyari, 7.7 km diameter) corners of

the quadrangle. Areas to the west of crater Dickinson and southwest of it, at crater Erika

(10.5 km in diameter), appear to have fragmental surface materials that have been redis-

tributed by eolian processes. Evidence for this includes east-west-oriented wind streaks

and diffuse patches of dark and bright materials to the west of Dickinson (between about

On the basis of an analysis of the global size-frequency distribution of impact craters.

a crater retention age of 800 Ma (McKinnon and others, 1997), 500 Ma (Schaber and oth-

ers, 1992; Phillips and others, 1992), or 300 Ma (Strom and others, 1994) for the present

surface of Venus was proposed. 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 Atalanta Planitia quadrangle. Therefore, attention must be focused

on the definition of geologic units and structures and on analysis of crosscutting, embay-

ment, and superposition relations among structures and units in order to establish the

cases tectonic features are such a pervasive part of the morphology of the terrain that it

becomes part of the definition of a unit. For example, our tessera unit is similar to several

members of the Olympus Mons Formation on Mars (aureole members 1-4), 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. 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 chose to map them as a unit.

TESSERA MATERIAL

Here we summarize the stratigraphic units and structures and their relations.

Although we have mapped tectonic structure independent of geologic units, in many

and ridge belts manifest compressional deformation (anticline and thrust faults).

similar to terrestrial tholeiitic basalt (Basilevsky and others, 1992).

terrain is completely obscured.

160° and 165° E.) and around Erika.

regional geologic history.

others, 1992a).

around tectonic fractures and scarps (for example, Greeley and others, 1992).

Ridged and Grooved Plains Material Ridged and grooved plains material (unit prg) is commonly deformed by somewhat broad (5–10 km wide) ridges tens of kilometers long. Although ridged and grooved plains

do not occur in direct contact with densely lineated plains, patches of these two units often occur spatially close to each other. The typical structural pattern of densely lineated plains is not seen within nearby occurrences of ridged and grooved plains. Thus, the emplacement of the later unit took place after the deformation of densely lineated plains. In the Atalanta Planitia quadrangle, this unit is arranged in linear outcrops or belts 50–100 km wide and 250–300 km long and is largely equivalent to the ridge belts of Squyres and others (1992). These belts are formed from preexisting flat plains. Ridged and grooved plains are interpreted to be volcanic plains materials deformed into ridgelike belts by compression. Ridged and grooved plains occur primarily in the southeastern and eastern parts of the quadrangle and represent westernmost extension of the ridge belt concentration in the Pandrosos Dorsa area (east of the map area). Occurrences are oriented predominantly NNE–SSW in the southern part of the Atalanta Planitia quadrangle, but in the northeastern corner of the quadrangle the strike of the ridge belts is NNW–SSE (Lukelong Dorsa). Shield Plains Material Shield plains material (unit psh) is in contact with groove belt material (unit gb) and

ridged and grooved plains material (unit prg) in the southeastern, northeastern, and northwestern parts of the quadrangle. At the contacts, the surface features of both groove belt and ridged and grooved plains materials are truncated and covered by material of shield plains. This relationship is the evidence for the young age of shield plains. 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), 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 and are likely to be the sources of the adjacent smooth plains. A small occurrence of shield plains material is seen in the core area of Earhart Corona and is surrounded by flowlike features radiating away from the occurrence. This is the only example in the Atalanta Planitia quadrangle where specific flow units are associated with the small edifices of shield plains. The unit is widely distributed in the quadrangle especially in its central part and in the southwestern (around Ananke Tessera) and northwestern (around Meskhent Tessera) parts of the quadrangle. Almost no concentrations of shield plains material occur along the eastern margin of the quadrangle, where the plains are likely buried by younger plains units. Some isolated shields occur where subsequent plains units embay shield plains and form kipukas (flooding the bases of the shields and leaving the tops exposed). As the radar brightness of the two units typically is different, this permits an estimate to be made of the thickness (about 100–200 m) of the margins of the embaying unit, as information exists on the topography of the shields

After emplacement of the earlier plains units (and locally the formation of groove belts; see following section), the most widespread plains unit in the quadrangle, wrinkleridged plains material, was emplaced. Throughout the quadrangle, evidence exists for embayment of all previous units by regional wrinkle-ridged plains material. This unit is composed of morphologically smooth, homogeneous plains material of intermediate dark to intermediate bright radar albedo complicated by narrow linear to anastomosing wrinkle ridges (a structural element) in 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 tens of kilometers long; in some areas, they may be smaller, whereas in others they are larger. Their trend typically varies locally even within one site. This material is interpreted to be regional plains of volcanic origin that were subsequently deformed by wrinkle ridges. Volcanic edifices and

Smooth Plains Material and Lobate Plains Material The youngest plains units in the stratigraphic sequence are characterized by distinctive lobate and digitate shapes and margins and by morphologically smooth surfaces commonly unmodified by wrinkle ridges or other structural elements. Typically, wrinkle ridges and older tectonic structures are embayed by material of these plains as it is seen, for example, east of Earhart Corona and at Baltis Vallis in the southeastern part of the quadrangle. Two plains units are recognized: smooth plains material (unit ps) of uniform, either low or moderate albedo and lobate plains material (unit pl), having internal elements arranged in parallel to sinuous to lobate radar bright and dark strips and patches and unit boundaries that are typically lobate. Both of these units are interpreted as complexes of lava flows undisturbed by subsequent deformation. Smooth plains material may be composed to some extent by redistributed eolian material. In the Atalanta Planitia quadrangle,

nating from distinct sources such as coronae and volcanoes.

CRATER MATERIALS Impact craters and related deposits are observed in several places in the quadrangle

(fig. 1). They are subdivided into crater material, undivided (unit c) and the proximal tex-

Several types and scales of features of compressional origin also are observed. Wrinkle ridges are seen throughout the quadrangle and are so important in the broad plains that they in part define and characterize wrinkle-ridged plains material. These features are mapped in a representative sense in terms of density and trend by individual wrinkle ridge and the general trends of these are represented in the units by symbols. Occurrences of ridged and grooved plains form 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) described a structure (ridge belts, RB) that 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

Flanks of two large volcanoes are visible within the Atalanta Planitia quadrangle and several coronae are seen there (fig. 1), the largest of which is the 560-km x 480-km Nightingale at the west margin of the map area. This structure and Earhart Corona, about 800 km north of Nightingale, is part of a corona cluster in Tethus Regio. Nightingale and Earhart Coronae are defined by an annulus of highly grooved and intensely deformed terrain. The coronae also are characterized by concentric and radial grabens and fractures both inside and along the margins of the annulus. In the core area of Nightingale Corona, both tessera material and densely lineated plains material occur. Nightingale and Earhart Coronae are surrounded by an extensive apron of flows of lobate plains material (unit pl) and smooth plains material (unit ps). Other coronae on Venus typically have an annulus made up of material resembling densely lineated plains broadly embayed by younger plains units (Basilevsky and Head, 1998; Ivanov and Head, 1998). The southernmost Mari Corona and the stellate fracture center of Ciuacoatl Mons (at about 53.5° N., 151.0° E.) are embayed by flows of lobate plains material, some of which appear to emanate from the coronae. On the basis of these observations, the structural deformation of the coronae apparently occurred early, with volcanism continuing in several cases until recently.

GEOLOGIC HISTORY The Atalanta Planitia area is one of several large, somewhat equidimensional lowland areas of Venus and is an important region for analysis of processes of lowland formation and volcanic flooding. Major questions include: What is the sequence of events in the formation and evolution of large-scale equidimensional basins on Venus? What are the characteristics of the marginal areas surrounding these basins? How do the units and implied geologic histories in both the basin and the marginal areas compare within Atalanta? When did the Atalanta Planitia basin and its marginal region form and is there any evidence that the basin represents a stage in the evolution of other terrain types, such as tessera? How do the units in Atalanta Planitia compare with each other and what information do they provide concerning models for Venus global stratigraphy and tectonic history? Here we discuss stratigraphic positions of units, their temporal correlations, 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 Atalanta Planitia in relation to models for the global

The stratigraphically oldest unit in the map area is tessera material, a high-standing, complexly deformed unit of which the largest outcrop is exposed in Ananke Tessera. Smaller massifs of tessera within the map area are represented by Meskhent Tessera at the west margin of the quadrangle and small tessera patches preserved mostly in the southern and northern parts—Mago-Halmi Tesserae—of the map area. Tessera is consistently embayed by younger plains material of apparent volcanic origin. The principal massif of Ananke Tessera shows chaotically organized narrow and broad ridges 5–15 kilometers across cut by numerous narrow and shallow grabens that are mostly orthogonal to the ridges. The same basic set of structures occurs within Meskhent Tessera. Consistent with observations made on regional (Bindschadler and others, 1992a) and global scales (Ivanov and Head, 1996), tessera material in Ananke and Meskhent 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 then underwent 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 (for example, Ivanov and Head, 1996). Whether this distribution is planetwide or regional or even local is unclear. No direct evidence exists in the map area for the duration of the formation with the characteristic structural pattern of tessera, but global crater studies (Ivanov and Basilevsky, 1993; Gilmore and others, 1996) suggest that it was of relatively short

duration (for example, tens of millions of years). Marginal to the tessera terrain and embaying it are plains that have been densely fractured (unit pdl) and in some cases have a structural fabric orientation similar to the latest phase of deformation in tessera (for example, Basilevsky and Head, 1995a, fig. 4). Along the northern margin of Meskhent Tessera, an east-west-trending band of densely lineated plains material is characterized by a very dense set of north-south-oriented structures. Features 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 are very dense and unidirectional in contrast to the orthogonal patterns of the tessera. The morphology and planimetric shape of the structures of densely lineated plains suggest that both tensile and shear stresses have been involved in the deformation of the plains. This unit is interpreted to be phases of tessera deformation. Densely lineated plains material is thus partly laterally equivalent to tessera material, and the northern margin of Meskhent Tessera and the east edge of Ananke Tessera are examples of such a transition. Densely lineated plains material makes up a small percentage of the area of our mapping but is widespread in the map area, suggesting an extensive presence in the subsurface. Following the emplacement and deformation of densely lineated plains material (unit

pdl), a less intensely deformed plains unit 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 and comparable to lunar mare arches of compressional origin) that are very pervasive from place to place. Occurrences of the unit apparently make up a very broad arc running generally in the north-south direction along the east edge of the map area. The unit occurs as broad arches (as much as 75–100 km across) striking northeastsouthwest in the south-central part of the map area and northwest-southeast in the northern 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 features is similar. Thus, the period during which this unit was formed and modified was characterized by emplacement of widespread volcanic plains and their subsequent deformation into broad arches with distinctive ridges and fractures. On the basis of its present topographic configuration, this unit and its deformation appear to have produced the second-order topography of the basin, 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 surround-The time of the formation of groove belts is poorly constrained in the map area. The

belts occur almost exclusively in the annuli of Nightingale and Earhart Coronae. In Nightingale Corona, some evidence suggests structures of groove belts cut tessera material and are embayed by wrinkle-ridged plains material. Tight spatial association of groove belts and coronae suggests that the formation of the belts is related to the development of coronae and could continue through a significant time interval. Groove belts are a few hundred kilometers wide and hundreds of kilometers long and occur predominantly in the eastern and southern parts of the map area. Topographically the groove belts represent local highs of the large corona annuli. Formation of the belts of grabens mark an episode of extension that was radially oriented relative to the core areas of Nightingale and Earhart Coronae and apparently unevenly distributed throughout Atalanta Planitia. Groove belts appear to cut some portions of shield plains, yet shield plains material (unit psh) is seen, in places, embaying groove belt material and forming in the depressions within the groove belts (for example, in Ciuacoatl Mons). Following emplacement and deformation of ridged and grooved plains material,

another distinctly different plains unit (shield plains, unit psh) was emplaced in many parts of the map area and is now preserved as extensive occurrences preferentially in the central part of the map area and around Ananke and Meskhent Tesserae and as patches in high areas elsewhere in the quadrangle. The abundant shield volcanoes and intershield plains that are characteristic of this unit are noticeably different from the volcanic style of both ridged and grooved plains and subsequent plains with wrinkle ridges. The extent of these vents indicates widespread local and shallow magma sources during the emplacement of shield plains material. 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 (unit prg) and apparently was emplaced on horizontal surfaces, which is suggested by the lack of systematic asymmetry of individual edifices (Kreslavsky and Head, 1999). Such asymmetry could be introduced if structures of shield plains (edifices) were formed on a regionally tilted surface. On the basis of topographic distribution of outcrops of subsequent units (wrinkle-ridged plains material and younger units), the shield plains material underwent some tilting after its emplacement. 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, which strongly suggests that shield plains material is mostly an older unit. The only exception to this is in the core area of Earhart Corona where a small occurrence of shield plains material is apparently in a geometric center of a field of lava flows that radiate away from an outcrop of shield plains material. This relation could mean that the edifices of shield plains probably were the sources for the lava flows. Subsequent to the emplacement of shield plains, the style of volcanism changed. Instead of abundant small shield volcanoes, broad units of plains materials, now regionally deformed by wrinkle ridges (units pwr₁ and pwr₂), were emplaced from sources that are now rarely visible. The presence of sinuous channels (a small segment of the largest chan-

nel on Venus, Baltis Vallis, is in the very southeastern corner of the map area; Basilevsky

and Head, 1996) and the wide extent of these units suggest emplacement in high-effusion-

rate eruptions from a few sources, in distinct contrast to the widespread and abundant

shield volcanoes just preceding this phase. At least several occurrences of unit pwr₂ occur along the eastern margin adjacent to later flows of lobate plains material (unit pl). One extensive occurrence of this unit in the southern part of the map area is associated with a large volcanolike source (48° N., 160° E.) just outside the southern margin of the Atalanta Planitia quadrangle. This suggests that regional deposition of the lower unit of wrinkle ridged plains material (unit pwr₁) 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 material outcrops and belts of ridged and grooved plains material. Their distribution is good evidence that most of the topography observed today was formed before the emplacement of the majority of wrinkle ridged plains material. However, the volcanic plains of units pwr₁ and pwr₂ were further deformed by the formation of wrinkle ridges subsequent to their emplacement; the central parts of deposits of these units are depressed up to a few hundred meters from surrounding marginal deposits of the same unit. Some wrinkle ridges in the eastern part of the map area are oriented generally consistently with the tectonic fabric and principle stress directions typical of ridged and grooved plains. Thus, the deformation recorded in units prg, pwr₁, and pwr₂ appears to be relatively consistent in structural trends but reflects a decrease in the intensity of shortening and defor-

In a few cases some smooth plains material (unit ps) similar to the underlying plains materials (unit pwr₁ and pwr₂) was emplaced at the periphery of the area of the Atalanta basin and is apparently unmodified by wrinkle ridges. In the northeastern corner of the map area, a large occurrence of smooth plains material is close to impact crater Dickinson. The surface of the plains there is characterized by wind streaks, which are suggestive of the redistribution of loose material. Thus, the smooth plains material may be related, to some extent, to the deposition and redistribution of debris material that was formed after

Near the end of emplacement of wrinkle-ridged plains material, extensive lobate and digitate flows (unit pl) originated from coronae and volcanoes along the margins of the Atalanta Planitia basin. Some of the flows were radial relative to coronae whereas the others flowed down the regional slopes into the basin. The sources of lobate plains material in the map area are Nightingale, Earhart, and Mari Coronae and Ciuacoatl Mons and intermediate volcanoes Melia Mons and Jael Mons, from which numerous flows emanate and extend down into the basin, following preexisting topography. No evidence exists for the deformation of these flows by wrinkle ridges, which suggests that the flows are either very recent and as yet undeformed or that wrinkle ridge deformation as a general phenomena ceased by this time. A few wrinkle ridges, which are visible, in some places, within areas of the lobate plains material (unit pl), apparently represent kipukas of structures deforming material of plains with wrinkle ridges (unit pwr₁). On the basis of the general decrease in tectonic deformation intensity as a function of time, we interpret the general absence of wrinkle ridges in lobate plains material to be the result of waning deformational forces. Despite the fact that these are the youngest flows in the map area, evidence from Nightingale and other coronae indicate that corona interiors and margins contain units equivalent to some of the earliest post-tessera plains units (for example, densely lineated plains material, unit pdl; Basilevsky and Head, 1995a, b) and that they thus started to form during this early period. In summary, volcanism at the time of the emplacement of lobate plains material (unit pl) switched from the basin interiors to the margins and from extensive floodlike plains units to digitate and lobate flows emanating from specific sources such as coronae and intermediate and large volcanoes. Coronae had apparently started to form at the same

time as earlier activity in the basin interior. Of the 26 impact craters seen in the map area (fig. 1, table 2), we observed only one example of an impact crater (Koidula, 64.2° N., 139.6° E., 67 km diameter) possibly embayed by volcanic activity (unit pl); no craters apparently are cut by tectonic structures. Thus, most impact craters appear to be younger than the regional plains materials. Rim heights of craters less than about 30 km in diameter should be <500 m (Sharpton, 1994). On the basis of the fact that no examples of craters embayed by pre-lobate plains units are observed and that the widespread deposits of wrinkle-ridged plains material are thought to be relatively thin, we interpret the lack of embayed craters to indicate that the plains units probably were 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, ridged and grooved plains, wrinkle-ridged plains material, and finally, to essentially no deformation of the latest flows of lobate plains. Trends in principal stress orientation suggest a relatively consistent post-tessera northwest-southeast and northeast-southwest principal compression axis orientation in the eastern part of the basin from early post-tessera through the emplacement of plains with wrinkle ridges. The topography of the basin in which Atalanta Planitia lies initially formed at the time of deformation of ridged and grooved plains (producing a series of smaller basins bounded by belts of unit prg) and continued to subside following partial filling of plains with wrinkle ridges. 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) in Atalanta Planitia, then changed style and was focused in the basin interior, where individual basins were filled by possible large volume eruptions, and finally, changed style and location, erupting from coronae and related features along the basin margins into the basin interior, where volcanism had apparently ceased.

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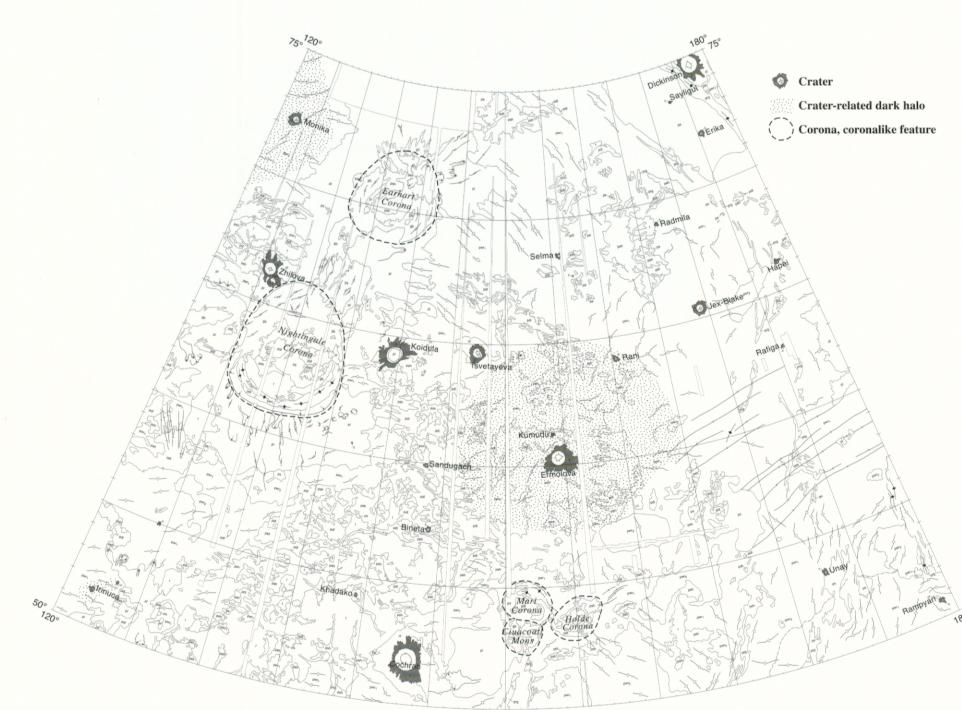


Figure 1. Distribution of impact craters and coronae in Atalanta Planitia quadrangle.

Table 1. List of large volcanoes in Atalanta Planitia quadrangle
 (from Crumpler and Aubele, 2000). 120° E. Melia Mons 63° N. 51° N. 121° E.

Table 2. List of impact craters in Atalanta Planitia quadrangle (from Schaber and others, 1998). 74.6° N. Sayligul 73.6° N. 172.9° E. Monika 72.3° N. 122.4° E. 72.0° N. 175.4° E. 167.0° E. 68.5° N. 155.9° E. 67.6° N. 157.2° E. 125.7° E. 178.0° E. 66.1° N. 65.4° N. 169.3° E. 147.4° E. 64.2° N. 139.6° E. 64.1° N. 160.4° E. 62.9° N. 175.6° E. Kumudı 61.3° N. 154.1° E. 60.4° N. 137.2° E. 59.9° N. 143.5° E. 57.3° N. 144.1° E. 124.5° E. 54.2° N. 139.3° E. 53.5° N. 172.7° E. 52.1° N. 123.2° E. Cochran 51.9° N. 143.4° E. Irinuca 51.4° N. 121.9° E. 50.6° N. 179.3° E.

Flow front—Arrow indicates flow direction

Rim of impact crater (>10 km diameter)

Rim of impact crater (<10 km diameter)

knowledge of the geophysics of Venus by analysis of venusian gravity.

The Magellan spacecraft orbited Venus from August 10, 1990, until it plunged into the

The Magellan spacecraft carried a 12.6-cm radar system to map the surface of Venus.

venusian atmosphere on October 12, 1994. Magellan had the objectives of (1) improving

knowledge of the geologic processes, surface properties, and geologic history of Venus by

analysis of surface radar characteristics, topography, and morphology and (2) improving

The transmitter and receiver systems were used to collect three datasets: synthetic aperture

radar (SAR) images of the surface, passive microwave thermal emission observations, and

measurements of the backscattered power at small angles of incidence, which were proc-

essed to yield altimetric data. Radar imaging and altimetric and radiometric mapping of

September 1992. Ninety-eight percent of the surface was mapped with radar resolution of

approximately 120 meters. The SAR observations were projected to a 75-m nominal hori-

zontal resolution; these full-resolution data compose the image base used in geologic map-

ping. The primary polarization mode was horizontal-transmit, horizontal-receive (HH), but

High-resolution Doppler tracking of the spacecraft was done from September 1992

with associated linear depressions. Remnants of preexisting plains can be about 950 orbits were obtained between September 1992 and May 1993, while Magellan others, 1993). Atalanta Planitia gravity and geoid data show that the lowland is character-

through October 1994 (mission cycles 4, 5, 6). High-resolution gravity observations from

additional data for selected areas were collected for the vertical polarization sense. Inci-

the venusian surface were done in mission cycles 1, 2, and 3, from September 1990 until

Corona, coronalike feature

Central peak of impact crater

dence angles varied from about 20° to 45°.

---/ Channel

ence locality: 51.5° N., 158.5° E. Interpretation: Lava flows subsequently

Lower unit—Plains material of generally low radar backscatter; commonly

Shield plains material—Plains material of high to low radar backscatter char-

Ridged and grooved plains material—Characterized by uniform and inter-

likely to be the sources of adjacent plains material

mottled locally. Modified by wrinkle ridges. Reference locality: 64.0° N.,

168.0° E. Interpretation: Lava flows subsequently deformed by wrinkle

acterized by abundant small shield-shaped features (a few up to 10–20 km

diameter) commonly having summit pits. Shields occur in clusters, giving

unit a locally hilly texture, and as isolated outcrops in relatively smooth

plains. Unit commonly occurs on densely lineated plains material; in pla-

ces crossed by wrinkle ridges. Reference locality: 59.5° N., 158.0° E.

Interpretation: Shields are interpreted to be of volcanic origin and are

mediate radar backscatter plains having generally densely spaced, sinuous

ridges up to 5–10 km wide and several tens of kilometers long. Arranged

in linear belts (250–300 km long and 50–100 km wide). Type locality:

37.7° N., 396.6° E.; reference locality: 54.5° N., 179.3° E. Interpretation:

intensely lineated by closely spaced narrow parallel lineaments 10-20 km

long and less than 1 km wide, anastomosing patterns in places; with a few

exceptions, typically radar bright due to dense fractures. Type locality:

48.5° N., 15.0° E.; reference locality: 53.5° N., 143.5° E. Interpretation:

Volcanic plains material very highly modified by fractures of probable

extensional origin. Local changes in fracture density suggest some resur-

Groove belt material—Characterized by numerous short and long curvilinear

subparallel lineaments that are typically wide enough to be resolved as

fractures and grabens. Forms curvilinear belts up to 500 km long and

150–200 km wide that are characterized by generally high topography but

Volcanic plains material deformed into ridgelike belts by compression

Densely lineated plains material—Predominantly flat plainslike material

deformed by wrinkle ridges

facing during formation