Geologic Map of the Bereghinya Planitia Quadrangle (V–8), Venus

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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 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 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 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 processed to yield altimetric data. Radar imaging and altimetric and radiometric mapping of the venusian surface were done in mission cycles 1, 2, and 3, from September 1990 until September 1992. Ninety-eight percent of the surface was mapped with radar resolution of approximately 120 m. The SAR observations were projected to a 75-m nominal horizontal resolution; 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 from about 20° to 45°.

High-resolution Doppler tracking of the spacecraft was done from September 1992 through October 1994 (mission cycles 4, 5, 6). High-resolution gravity observations from about 950 orbits 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. Observations from an additional 1,500 orbits were obtained following orbit-circularization in mid-1993. These data exist as a 75° by 75° harmonic field.

MAGELLAN RADAR DATA

Radar backscatter power is determined by the morphology of the surface at a broad range of scales and by 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, because 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, a rapid increase in reflectivity exists at a certain critical elevation, above which high-dielectric minerals or coatings are thermodynamically stable. This effect 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 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

The Bereghinya Planitia quadrangle (V–8) of Venus is bounded by 25° and 50° N. latitude, 0° and 30° E. longitude. It is one of 62 quadrangles covering the entire planet at a scale of 1:5,000,000. The quadrangle derives its name from the plains region Bereghinya Planitia, most of which falls within the boundaries of the quadrangle. Bereghinya are benevolent protective female spirits in East Slavic mythology. These spirits were considered as guardians of the home, and traditional homes commonly had carvings of Bereghinya around their windows. In addition, these spirits were associated with riverbanks, so some of them were envisioned as being women with fish tails, similar to mermaids.

The Bereghinya Planitia quadrangle comprises mostly plains materials that have been highly modified by younger structures, mostly related to coronae. The map area contains all or part of 22 named coronae, 4 named deformation belts, and 2 major lava channel systems having extensive associated volcanic flows. In addition, other valles, a deformation belt, and coronae occur within the quadrangle but are unnamed. The quadrangle hosts 24 impact craters and 6 bright splotches believed due to explosive destruction of bolides in the atmosphere

(Campbell and others, 1992; Ivanov and others, 1992). Many of the impact craters have associated dark halos or parabolas, and four are accompanied by fields of secondary craters. Also present is a complex array of faults, fractures, and wrinkle ridges.

The quadrangle is geologically interesting primarily because of the large population of coronae, many of which are connected to each other by belts of closely spaced, complex wrinkle ridges producing a spiderlike pattern in which the "bodies" are coronae and the "legs" are the connecting belts. These coronae were named "arachnoids" by members of the Soviet Venera team (Barsukov and others, 1986). The problems of more than local interest include the kinematics and dynamics of the arachnoids, the structural and volcanic evolution of the coronae, and the age of the widespread background plains relative to structures and other material units.

METHODS AND DATA USED

Mapping was based on both hardcopy and digital versions of Magellan synthetic aperture radar (SAR) data. In cycle 1, the SAR incidence angles for images taken of the Bereghinya Planitia quadrangle ranged from 33° to 44°. Mapping was carried out in Adobe Illustrator using a digital controlled mosaic of SAR images prepared by the U.S. Geological Survey. Individual tiles of 75 m/pixel FMAPs were imported into Illustrator as needed to provide greater detail. Also helpful were 1:1,500,000 photographic prints of 12° x 12° or 12° x 18° (depending on latitude) FMAPs, also provided by the U.S. Geological Survey. Topographic information was utilized in two ways: (1) as a color base layer in Illustrator that could be accessed simply by turning off the SAR base mosaic in the next higher layer, and (2) as pseudo-stereo versions of 225 m/pixel compressed-once mosaicked image data records (C1–MIDRs) created at the U.S. Geological Survey by using Magellan altimetry to generate artificial parallax on the SAR C1–MIDRs. The pseudo-stereo images were used to generate anaglyphs in Adobe Photoshop. For local detail, the original altimetry data were gridded in SURFER to prepare contour maps, topographic images, and three-dimensional mesh diagrams.

Stratigraphic material units were defined primarily by their relative radar brightness and surface textures, although crosscutting relations with structures, relative ages, and apparent association with topographic or structural features also were considered where appropriate and useful. Because the SAR images were all taken with intermediate to large incidence angles, the relative radar brightness of the various map units relates primarily to surface roughness at a scale comparable to the radar wavelength (12.6 cm). Characteristic values of important radar properties (radar backscatter coefficient, emissivity, reflectivity, and root-mean-square slope) were calculated for material units using programs provided by Campbell (1995). However, these properties were not used in the original unit definitions, which were based entirely on visual properties apparent in the SAR images. The radar parameters provide information about the nature (grain size, surface texture, dielectric constant) of the materials making up a map unit, and thus in some instances can contribute to determining the most likely origin of the unit.

STRATIGRAPHY

The stratigraphic units in the Bereghinya Planitia quadrangle are grouped into five broad categories according to terrain type: tessera, plains, coronae, miscellaneous flows and domes on plains, and impact craters. Twenty-seven units have been defined: one tessera unit, five plains units, seven flow units associated with coronae, nine miscellaneous flow and dome units, and five impact-crater units. Most unit names are based on characteristics visible on SAR images. Relative ages of units were determined primarily by embayment relations and truncation of structures at contacts; locally the relative ages of units not in contact with each other can be determined relative to a third unit or to structures. Quantitative radar properties for some units or types of units are summarized in table 1 and are compared (fig. 1) with the average scattering of the Venus surface as described by the Muhleman law (Muhleman, 1964).

TESSERA MATERIAL

Scattered within the Bereghinya Planitia quadrangle are radar-bright inliers within younger plains materials that are comparable to tessera terrain, as defined from Venera images (Basilevsky and others, 1986). All tessera material (unit t) has been intensely deformed into at least two sets of structures at high angles to each other. Some of these structures are grabens that are large enough for diagnostic criteria to be clearly visible on the Magellan images. Within most tessera inliers are small patches of radar-dark intratessera plains material. Many of these are actually continuous with the plains materials surrounding the tessera; those that are isolated from the surrounding plains are too small to map separately. The tessera inliers are heavily embayed by surrounding plains material, and the plains material floods the large grabens and abruptly truncates all other structures that crosscut the tessera material. All of the tessera inliers are in contact with, and older than, regional plains material (unit pr), and thus tessera material must be older than all materials younger than regional plains material. Bright plains material (unit pb), is in contact with tessera material at only one locality in the quadrangle (46˚ N., 0˚ E.). However, bright plains material is in contact with and younger than tessera material in the adjacent Sappho Patera quadrangle, where the unit is called “lineated plains material” (McGill, 2000). In addition, bright plains material is consistently less deformed than tessera material. Although tessera material is almost certainly older than all other materials in the quadrangle, it is not possible to determine if it represents remnants of terrains that are fundamentally different and much older than regional plains material or if it is simply highly deformed plains material that is not significantly older than regional plains material. Furthermore, determining if the various patches of tessera contain materials of similar age is not possible; in fact, these materials could be of widely differing ages.

PLAINS MATERIALS

Most plains materials are characterized by low to intermediate brightness on the SAR images. Some of the geologic units mapped in the Bereghinya Planitia quadrangle are the same as those mapped in the adjacent Sappho Patera quadrangle (McGill, 2000), especially plains units, all of which were originally defined in the Sappho Patera quadrangle. Exposures of three plains units sit astride the boundary between the quadrangles, and thus these units are physically continuous from one quadrangle to the other. The three continuous units are regional plains, low-relief shield plains, and homogeneous plains materials.

Scattered about the quadrangle are numerous inliers of bright to extremely bright plains material (unit pb). All inliers of bright plains material are embayed by, and thus older than, the surrounding regional plains material. Bright plains material is generally deformed by one set of linear features (probably faults or fractures) that are truncated at contacts with surrounding plains materials. Locally, these linear features are closely spaced, forming a fabric that is penetrative at map scale. The large grabens that cut most areas underlain by tessera material are generally not present in inliers of bright plains material. The larger areas of bright plains material commonly occur on low rises that are surrounded by younger regional plains material. For many small bright patches on the plains, determining whether the brightness is due to the presence of bright plains material or to locally enhanced fracturing of the younger regional plains is difficult, suggesting that the bright plains material simply may be older, rougher, and generally more deformed plains material that otherwise is not fundamentally different from regional plains material.

Most of the Bereghinya Planitia quadrangle is underlain by regional plains material (unit pr). Regional plains material is by far the most widespread unit in the quadrangle, and it is characterized by a wide range of backscatter values that overlaps the backscatter values for most other units in the quadrangle (table 1, fig. 1). Regional plains material embays tessera and bright plains materials and is in turn embayed by flows derived from Gula Mons, by flows from many of the coronae in the quadrangle, by flows derived from valles, by flows associated with some shield fields, and by flows associated with domes. Scattered small volcanic edifices are common on regional plains material. Wrinkle ridges are nearly ubiquitous on regional plains but of widely varying abundance and brightness on SAR images. Because regional plains material is the dominant material unit mapped and because it is in contact with all other mapped materials, it is used as a local stratigraphic reference. This has been done fully recognizing that not all areas of regional plains need have formed at the same time; in fact, emplacement of this unit possibly occurred over an interval as long as 400 million years, which is a significant fraction of the mean surface age of the planet (for example, Hauck and others, 1998). However, the sparse crater population will not allow a credible estimate of the length of time involved. Nevertheless, defining time as pre-, syn-, and post-regional plains is useful and important because it provides a sense of crustal evolution in relative time.

Numerous large and small patches within regional plains material are characterized by an intricate array of bright lineations defining either a grid or a cellular pattern at a scale of one to several kilometers. In places, surrounding regional plains material appears superposed on this pattern, but more commonly the pattern simply loses sharpness so that contacts are gradational. These areas are indicated by a pattern overlay. The grid and cellular patterns of lineaments may be primary features of specific flows or portions of flows within the plains. At least some of the areas having a cellular pattern contain very closely spaced, small edifices, and thus the cellular pattern is probably due to fracturing around these edifices. Grid patterns present on otherwise typical plains material present a significant problem of scale because their dimensions are much greater than probable analogs on Earth (Johnson and Sandwell, 1992).

Completely enclosed within regional plains material are three areas mapped as low-relief shield plains material (unit psl). These areas appear superficially similar to the brighter areas included in regional plains material. However, low-relief shield plains are exposed on low rises having a relief of a few hundred meters. These rises are characterized by digitate and lobate flow lobes, and two of the three also have clearly visible source calderas. Low-relief shield plains material is superposed on regional plains material, but it formed before the development of all sets of wrinkle ridges present on the regional plains.

Dark plains material (unit pd) is present in a large area along the eastern boundary of the quadrangle. It occurs in a very shallow, irregular depression within regional plains. Dark plains material truncates lineations in adjacent regional plains material and ponds against some of the wrinkle ridges superposed on regional plains material. Other wrinkle ridges cross the contact between dark plains and regional plains materials. Flows from two unnamed valles are superposed on dark plains material within the quadrangle. The low radar backscatter is due to a smooth surface (table 1).

Scattered about the quadrangle, most notably in the southeast corner, are areas having a bland, homogeneous texture and uniform, intermediate radar brightness. These areas are mapped as homogeneous plains material (unit ph). The contacts of homogeneous plains material are locally wispy, suggesting some modification by wind action. Homogeneous plains material truncates structures within bright plains material. Its age relative to regional plains material is less clear, but locally the contacts of homogeneous plains material appear affected by wrinkle ridges on regional plains material, implying that the homogeneous plains material is younger.

CORONA MATERIALS

Of the 29 coronae and coronalike structures in the Bereghinya Planitia quadrangle, 21 have mappable flows associated with them, and 1 additional structure, Ba'het Corona, has flows outside the quadrangle boundaries. Flows from four coronae (Onatah, units fcO_1 and fcO_2; Ponmakya, unit fcP; Kostroma, units fcK_1 and fcK_2; and Ilmatar, unit fcI)) are separately named because they yield useful relative-age information. All other corona flows are included within corona flows, undifferentiated (unit fcu). Most flows from coronae show digitate and lobate shapes to some degree, but some of these tend to lose distinctness in places so that defining the exact limit of a corona-derived flow field is commonly difficult. In general, the corona flows having high backscatter values are most obviously superposed on regional plains material. Corona flows that exhibit uncertain contacts with regional plains material have backscatter values that are very similar to backscatter values of regional plains material. The mapping has been conservative in this respect; that is, only where it is possible to trace the flow shapes from a corona out onto the surrounding plains have these flows been mapped as corona derived. Much of the material included within regional plains material probably is corona derived, but demonstrating this conclusively is not possible. Two coronae (Onatah and Kostroma) have sharply defined, radar bright digitate flows in addition to the less distinct shapes that generally characterize corona flow fields. Location, diameter, and key geologic relations for all coronae are summarized in table 3. All corona flows within the Bereghinya Planitia quadrangle appear to be superposed on regional plains material, or else are gradational with them, although the relative ages are locally difficult to determine. As will be discussed in the structural geology section, concentric and radial structures of coronae all cut regional plains material, although for some coronae these structures also cut an apparently older unit that is mapped as bright plains material. Generally, corona structures are also younger than corona flows. These observations imply that most corona flows are younger than or the same age as regional plains material and that the coronae as structures are dominantly post-regional plains material. Flows from valles are in contact with corona flows at only one locality; there, flows from Bayara Vallis are clearly superposed on flows from Sulis Corona. Very few data exist to relatively date the coronae. Flows from Yaroslavna Corona are superposed on a complex bundle of wrinkle ridges that in turn cuts flows from Cavell Corona, implying that Yaroslavna flows are younger than Cavell flows. Cavell flows cross the topographic rim of corona d, indicating that corona d is younger than Cavell Corona. Onatah Corona flows are superposed on flows from Audhumla Corona, and Onatah flows also truncate structures associated with Sigrun Fossae.

MISCELLANEOUS DOME AND FLOW MATERIALS

Nine miscellaneous dome and flow units are mapped. These range from areally important units such as vallis flows and shield flows to features occurring at only one locality. All of these units are younger than regional plains material except some exposures of shield flows and possibly some domes.

Occurring as scattered exposures of varying sizes throughout the quadrangle are areas of shield flows (unit fs) that are related to clusters of small edifices, most of which are shield volcanoes. These clusters of edifices have been referred to as "shield fields" (Aubele and others, 1992). Not all small edifices occur in clusters, and not all clusters of edifices have an associated flow field, but the Bereghinya Planitia quadrangle contains a significant number of flow fields areally associated with shield fields. Shield flows have, on average, very similar radar backscatter to regional plains material. Wherever shield flows are in contact with corona flows and corona structures the shield flows are younger. An especially convincing example of this is found in the northwest corner of the quadrangle, where shield flows are superposed on structures related to Ba'het and Vasudhara Coronae. The quadrangle contains clear examples showing shield flows that are older than regional plains material, as well as clear examples showing shield flows that are younger than regional plains material. However, relative ages of shield flows and regional plains material are commonly ambiguous because both are transected by the same sets of wrinkle ridges. Thus individual areas of shield flows could be older, younger, or the same age as adjacent regional plains material.

Scattered about the quadrangle are several volcanic domes and shields (unit d) ranging up to about 35 km in largest diameter. The age of these domes relative to regional plains material is generally not possible to determine directly. However, some domes have associated dome and shield flow material (unit fd) that is superposed on regional plains material, whereas others appear to be partially buried by regional plains material.

At several locations digitate or lobate flows superpose regional plains material. These flows have no obvious source, and they are characterized by a more homogenous texture and backscatter only slightly higher than adjacent regional plains material. These flows are mapped as flow material, undifferentiated (unit f). At one locality (14.5°–15° E., 34.5°–35° N.) very small, digitate flows have a vermiform texture at subkilometer scale and very high radar backscatter. These flows, mapped as textured flow material (unit ft), are superposed on regional plains material. The source for these flows is not apparent.

In the southwest corner of the quadrangle are long, narrow digitate flows derived from Gula Mons, which is southwest of the Bereghinya Planitia quadrangle. These flows have high backscatter, but one of them also has a radar-dark border, suggesting that the flow is rough in the center but smooth along the edges. Gula flow material (unit fG) is superposed on regional plains and also floods north-south grabens that cut regional plains. Ejecta from crater Browning is superposed on one of these flows.

In the northeastern part of the quadrangle are extensive flows derived from lava channels, two of which have been assigned names. These flows are generally digitate and have backscatter values ranging from much lower to much higher than the backscatter values of adjacent regional plains material. Three units are mapped: Bayara Vallis flow material (unit fBa), Belisama Vallis flow material (unit fBe), and unnamed vallis flow material (unit fv). These flow materials are among the youngest materials in the quadrangle, superposing regional plains material, dark plains material, and all corona flows and most corona structures they contact. They also are superposed on most structures but have been deformed locally by some structures related to Aušrā Dorsa and by sparse wrinkle ridges.

IMPACT CRATER MATERIALS

Deposits of 24 impact craters occur in the quadrangle. The craters range in diameter from 3.5 km (Elenora) to 81.7 km (Mona Lisa). Location, size, and general characteristics of these craters are summarized in table 2. Five impact-crater units are included on the map: crater material, undifferentiated (unit c), crater flow (outflow) material (unit cf), and crater floor materials, divided into three units on the basis of radar backscatter—dark crater floor material (unit cfd), intermediate crater floor material (unit cfi), and bright crater floor material (unit cfb). The three crater floor units represent differences in surface roughness of the floor materials; these have been distinguished in order to record any correlation between floor brightness and overall level of crater freshness (table 2). Seven craters have bright floors, which have radar backscatter values between –7.5 and –11.4 dB (mean = –9.7 dB); twelve craters have intermediate floors, which have radar backscatter values between –12.5 and –16.3 dB (mean = –13.9 dB); and four craters have dark floors, which have radar backscatter values between –17.5 and –21.1 dB (mean = –18.6 dB); Elenora is too small to resolve the floor separately. Four craters have associated secondary craters, and where these define a discrete field or chain they are delineated on the map by a dashed line and the letter "s."

In addition to the 24 craters, the quadrangle includes 6 splotches inferred to result from explosive destruction of bolides in the Venus atmosphere (Campbell and others, 1992; Ivanov and others, 1992). These splotches occur as diffuse bright patches on the surface, generally with a vague circular pattern in the center. All six splotches occur in the southwestern part of the quadrangle.

All of the craters and splotches are younger than regional plains material. The only possible exception to this statement is the crater Mona Lisa, the largest and most degraded crater in the quadrangle. The arguments for an age younger than regional plains will be presented below, as will age relations of most craters with other units and structures. The craters will be discussed in latitude order, north to south.

Kauffman: The ejecta from Kauffman is somewhat asymmetrically distributed, which suggests a possible oblique impact from the northwest or west-northwest. The crater flow to the north of Kauffman ponds against narrow ridges that are part of Aušrā Dorsa.

Kemble: The asymmetry of ejecta from Kemble suggests an oblique impact from the west. Crater flows are restricted to the eastern downrange side of the crater. These flows flood northeast-trending grabens that are part of Sigrun Fossae. On the west, Sigrun Fossae structures cut the rim and ejecta of Kemble.

Elenora: This small, irregular crater is superposed on flows from Onatah Corona, which are among the youngest materials in the quadrangle. For a small crater, Elenora has a surprisingly large and complete dark halo.

Chubado: Chubado is a small, irregular crater that occurs on the broad ridge that connects Audhumla and Ba'het Coronae. This ridge is characterized by a complex array of bright lineaments; those trending northwest, parallel to the trend of the ridge, are superposed by Chubado ejecta, whereas those trending slightly west of north, and thus that transect the ridge obliquely, cut Chubado ejecta.

Prichard: Ejecta from Prichard are symmetrical about the crater. Although crater flows at Prichard are not apparent, some diffuse deposits having backscatter slightly above that for the local regional plains could be crater flows rather than simply representing normal variability of regional plains backscatter. Prichard ejecta is superposed on wrinkle ridges making up the belt that connects Audhumla Corona to Kostroma Coronae.

Ariadne: Ariadne is astride the boundary between the Bereghinya Planitia and Sedna Planitia quadrangles. Its ejecta is symmetrical around the crater. A few secondary craters are present within the Bereghinya Planitia quadrangle. A long crater flow extending southward from Ariadne may be cut by east-west-trending wrinkle ridges, although the evidence is somewhat ambiguous.

Ruth: Ruth has nearly symmetrical ejecta that yields ambiguous age relations with wrinkle ridges on the surrounding regional plains.

Talvikki: Talvikki ejecta distribution is nearly symmetrical. Wrinkle ridges on surrounding regional plains appear to cut Talvikki ejecta.

Lena: The ejecta from Lena is slightly asymmetrical, which suggests a possible oblique impact from the south-southwest. The crater is superposed on the belt of wrinkle ridges that extends southeastward from Yaroslavna Corona.

Stina: Stina ejecta approaches a butterfly pattern, which indicates oblique impact from the east-southeast. Northwest-trending wrinkle ridges cut crater flows from Stina.

Esterica: This small doublet crater provides no useful stratigraphic information.

Wilma: Ejecta from Wilma is somewhat asymmetrical, which suggests oblique impact from the southwest. Most crater flows are on the northeast side of the crater.

Ayisatu: The ejecta from Ayisatu forms a highly asymmetric butterfly pattern, which indicates oblique impact from the north-northwest. The ejecta is superposed on north-south-trending wrinkle ridges.

Melanka: Melanka is a doublet crater having highly asymmetric ejecta, which indicates oblique impact from the northeast. Crater flows occur to the west and southwest. Ejecta appears to be superposed on north-south-trending grabens.

Noreen: Ejecta from Noreen is approximately symmetrical about the crater. Noreen is superposed on structures in the belt that links corona f, Bécuma Mons, Dzuzdi Corona, and Cavell Corona. Noreen is the apparent source of a band of alternating light and dark streaks that extends for about 900 km westward from the crater.

Edgeworth: Except for a small gap in the ejecta blanket northeast of Edgeworth, the ejecta from Edgeworth is approximately symmetrical. Edgeworth ejecta is superposed on northwest-trending wrinkle ridges. The crater lies within the horseshoe-shaped ridge that defines the highly irregular corona f. Edgeworth is the apparent cause of a large, radar-dark parabola that overlaps with the streaks from Noreen. The parabola is an area of relatively low emissivity (fig. 2).

Defa: The crater rim appears incomplete to the southwest, and most ejecta and flow materials occur to the northeast, both suggesting oblique impact from the southwest. Crater flows flood north-northeast-trending grabens. Defa is superposed on flows from Ponmakya Corona.

Mukhina: Except for a small gap in the south-southwest, the ejecta from Mukhina is approximately symmetrical. Secondary craters occur mostly to the north, which, with the ejecta gap, suggests a possible oblique impact from the south-southwest.

Halima: Halima ejecta forms a distinctive butterfly pattern, which indicates oblique impact from the south-southeast. Ejecta appears to be both superposed on and cut by north-south-trending grabens.

Browning: Ejecta from Browning approaches a butterfly pattern, which indicates oblique impact from the southwest. Secondary craters are abundant on all sides of the crater except to the southwest. The crater appears to be superposed on wrinkle ridges present on the surrounding regional plains. It also is superposed on one of the flows from Gula Mons.

Kafutchi: This doublet crater has one member that is more than twice the size of the other. Kafutchi occurs within Beyla Corona, and north-south lineations characteristic of the interior of Beyla cut the crater.

Bachira: Bachira ejecta is approximately symmetrical. Relations with wrinkle ridges are ambiguous.

Ferber: Ferber ejecta is approximately symmetrical. Secondary craters occur around the entire crater except to the southeast. To the west are both a dark parabola and bright/dark streaks that extend for more than 300 km away from the crater.

Mona Lisa: Mona Lisa is a double-ring structure having ring diameters differing by about a factor of two. The interior of the structure consists of dark floor material that superficially resembles the regional plains that occur external to the crater. To the east, the plains material is homogeneous plains, and whether a contact exists between homogeneous plains material and crater flows within this relatively bright area is not clear. To the south, a contact is mapped between crater flows and homogeneous plains material, but which is younger is not known. However, along the west and northwest sides of Mona Lisa the relations seem to be clear—the ejecta is superposed on regional plains material. Wrinkle ridges cut Mona Lisa crater flows to the south and northwest. Finally, the dark material on the floor of Mona Lisa is characterized by a "cellular" pattern of wrinkle ridges, which is geometrically different from the more rectilinear sets of wrinkle ridges on the regional plains.

STRUCTURAL GEOLOGY

INTRODUCTION

The Bereghinya Planitia quadrangle includes a very complex array of structural assemblages and individual structural elements. Assemblages include deformation belts of various types, graben swarms, fabrics of narrow, radar-bright lineaments, and structures associated with coronae. Individual structural elements include radar-bright lineaments, grabens, wrinkle ridges, ridges of deformation belts, and broad, low ridges. Some of these individual structural elements can be conveniently described as part of the discussion of structural assemblages; others require separate treatment. The structural assemblages are considered first.

DEFORMATION BELTS

The quadrangle includes all or parts of five deformation belts: Sigrun Fossae, Aušrā Dorsa, Hera Dorsa, Tomem Dorsa, and a small, unnamed belt centered at about 46.5° N., 26° E. Sigrun Fossae is a complex northeast-trending belt of lineaments and grabens that is mostly within the Fortuna Tessera quadrangle to the north. Where the belt enters the Bereghinya Planitia quadrangle between 15° and 20° E. it is about 250 km wide and includes both closely spaced belt-parallel grabens and a penetrative fabric of north-south-trending to north-northwest-trending lineaments. The belt fans southward and ends at about 47° N., where it merges with structures associated with Audhumla Corona. The fanning results in some belt-parallel grabens on the west side of the belt curving toward an east-west trend and some on the east side of the belt curving toward a north-south trend. The topography in the general area of Sigrun Fossae (fig. 3) does not relate to the structural elements or trends of the belt, and thus no belt-scale topography is associated with Sigrun Fossae. Faults and lineaments of Sigrun Fossae cut bright plains material and, locally, regional plains material but are truncated by flows from Onatah Corona and Bayara Vallis. Sigrun structures are both older and younger than crater Kemble, demonstrating that deformation has been progressive.

Aušrā Dorsa is a northeast-trending composite belt that is about 75 km wide where it enters the quadrangle at 27° E. Immediately to the north, in the Fortuna Tessera quadrangle, it merges with a larger belt that trends north-south. A narrow moat extends along both sides of Aušrā Dorsa for almost its entire length so that it is generally elevated above the immediate surroundings (fig. 3). Aušrā Dorsa widens and the individual structural elements become more widely spaced southward, and it cannot be followed as a discrete structural feature south of about 44° N. The belt includes belt-parallel ridges of two scales, and transverse northwest- to east-west-trending lineaments. Some of the ridges appear to be typical wrinkle ridges having widths less than 1 km; others are broader, gentler features that are up to about 8.5 km wide. The latter are inferred to be gentle ridges because of the gradual change from radar-bright to radar-dark across them, but the widest of these also show relief on the anaglyph at C1–MIDR scale. Both the wrinkle ridges and the broader ridges are consistent with contraction normal to the length of the belt. The transverse lineaments are generally too narrow to permit resolving their geometry, but some are wide enough to suggest that they are grabens. Thus these structures are assumed to be of extensional origin. The lineaments of Aušrā Dorsa deform regional plains material, but age relations for the ridges are ambiguous. Flows from Belisama Vallis are diverted by Aušrā Dorsa, but the transverse extensional lineaments cut both the belt and the vallis flows.

The small deformation belt centered at about 46.5° N., 26° E. is 150 km long and 25 km wide at its widest point. The material of the belt is mapped as bright plains (unit pb). No overall topography is associated with the belt. Within it, however, are gentle ridges of the type found within Aušrā Dorsa that are up to about 3 km wide. Flows from Edda Corona pond against one of these gentle ridges, and the entire belt appears embayed by regional plains material.

Tomem Dorsa consists of a north-south-trending bundle of closely spaced wrinkle ridges in the southwestern part of the quadrangle. Tomem Dorsa differs from the belts of wrinkle ridges that connect many of the coronae in Bereghinya Planitia only because it is not related to coronae. Hera Dorsa is defined by very subtle, northwest-trending ridges of regional plains material separated by equally subtle northwest-trending troughs occupied by dark plains material.

Many of the coronae in the Bereghinya Planitia quadrangle are connected by belts of closely spaced structures that commonly reside on broad, subtle ridges, many of which show clearly even on a small-scale topographic map (fig. 3). Because some coronae are connected to others in more than one direction, the overall pattern reminds one of a spider, hence the name arachnoids (Barsukov and others, 1986), a term that should be avoided because it masks the basic similarity of the features in this quadrangle to coronae elsewhere on Venus (Stofan and others, 1992, 1997). However, the nature of the structures occurring on the “spider legs” is of some importance. Many of the individual structural elements within the belts are too narrow to resolve their geometry. Most of these are sinuous and thus are inferred to be wrinkle ridges similar to those found on the plains over most of the planet. However, they are much more closely spaced than is generally the case. The most interesting structures in the belts are sinuous, ropy lineaments that commonly include two bright strands, each about the same width as a typical wrinkle ridge, that are either parallel to each other or intricately braided. Locally, these braided pairs appear to lie on a very subtle ridge that is the width of the braided pair or wider.

CORONAE

The Bereghinya Planitia quadrangle contains an unusually large assemblage of coronae and coronalike features. These range in size from Kumang Corona, which has a diameter of 41 km, to Beyla, which has a long diameter of 326 km and a short diameter of 236 km. In all, the quadrangle contains 29 coronae, of which 5 (Ba'het, Cavell, Sand, Trotula, and Yaroslavna) were originally designated as paterae. In addition, seven coronae and coronalike features are unnamed; these are designated on the map by lower-case letters, a–g (from north to south). Location, size, and key characteristics of each feature are presented in table 3.

As discussed above, complex belts of wrinkle ridges link many of the coronae, thus forming clusters and chains of coronae. One of the corona chains is continuous with the deformation belt Aušrā Dorsa. The coronae in the Bereghinya Planitia quadrangle exhibit a wide range of structural and topographic characteristics. Most are defined by both concentric topographic rims and fracture rings, although the two do not coincide for some coronae. Topographic rims are actually ridges that are elevated above the surrounding plains as well as above the centers of coronae. Fracture rings consist mostly of radar-bright lineaments that are too narrow to resolve their geometry, but also included are well-defined grabens. Commonly, the bounding rims and rings do not completely encircle the structure. Most of the coronae are depressed in their centers (fig. 3), but some show no obvious topography (for example, Onatah and a) and one (e) has a central mound rather than a depression. Some central depressions are simple (fig. 4), others include more complex interior topography (fig. 5). Most of the coronae are sources of at least some flows, but a few have no associated volcanic material. Generally, flows from different coronae are not in contact with each other, a situation that complicates determining relative ages. The sizes of coronae are difficult to define in most instances, in part because of the incompleteness of many topographic rims and fracture rings, in part because of the irregular shapes of many of these features. Fracture rings and topographic rims have finite widths; diameters quoted in the table were measured from the centers of the fracture bands defining the coronae rather than from the inner or outer edge of these bands and from ridge crest to ridge crest of topographic rims. Concentric or radial structures associated with all of these coronae, except possibly Ba'het Corona, deform regional plains material (unit pr). Some also deform bright plains material. The coronae are described below in order from north to south across the quadrangle.

Onatah Corona: Onatah is a large feature characterized by very poorly developed concentric structure, no distinctive topography, and very extensive flows, some of which extend north of the quadrangle boundary. The main source for flows is on the eastern and southeastern rim of the structure, and flows from this source fill the central region of the corona and cover a large area mostly to the east, south, and north. No flow sources are apparent in the central region of the corona. Flows to the east and south are largely confined north of an older low, arcuate ridge that joins Sigrun Fossae and Audhumla Corona to Ba'het Corona. Onatah flows have a lower density of wrinkle ridges than plains materials and flows from other coronae. Radial and concentric fractures occur only along the western side of the corona. These fractures cut Onatah flows. The radial fractures link Onatah Corona to Ba'het Corona.

Damona Corona: This corona is a complex, kidney-shaped structure having limited flows, most of which are in the interior of the corona. Damona is bounded by an incomplete ring of concentric fractures and a partial topographic rim on the northwest side only. Corona fractures do not appear to cut the flows derived from the corona.

Ba'het Corona: Ba'het is an irregular, elongate corona, most of which is west of the Bereghinya Planitia quadrangle. The corona is almost completely bounded by a fracture ring but has a topographic rim only along the north side. The interior contains a large patch of radar bright, densely lineated bright plains material (unit pb), which suggests that Ba'het is older than regional plains material or that the bright plains material survived the process that formed the corona. No flows from Ba'het are apparent within the Bereghinya Planitia quadrangle, but flows derived from Ba'het occur west of the structure. These flows are cut by both radial and concentric Ba'het fractures. The interior of the corona is flooded with younger shield flows and flows from Onatah Corona.

Edda Corona: Edda Corona lies at the north end of the small, north-northwest-trending ridge belt discussed above that consists of bright plains material (unit pb). About half of its circumference is defined by a topographic rim and a fracture ring that are coincident. Flows are moderately extensive, and these appear to pond against ridges in the ridge belt and also against northeast-trending wrinkle ridges that deform regional plains material, but they are cut by concentric corona fractures.

Audhumla Corona: This corona has an intensely fractured northern border but essentially no fractures defining its southern border. No topographic rim is evident. The intensely fractured material of the northern border is mapped as bright plains material (unit pb). Separating Audhumla structures from structures in Sigrun Fossae is very difficult because fossae structures intersect and merge with the fractures that form the northern border of the corona. The relation is one of mutual crosscutting, and thus whether Audhumla is older than, younger than, or the same age as Sigrun Fossae is not possible to determine. Flows are not extensive, but because they are superposed by flows from Onatah Corona they are probably more widespread beneath the younger unit. Structures related either to Audhumla or to Sigrun Fossae cut Audhumla flows.

Corona a: This corona is a poorly defined structure having no topographic rim and an incomplete, narrow fracture ring. Corona a lies partly within Aušrā Dorsa, and its eastern half is deformed by ridges and lineaments that are part of the dorsa. No apparent flows derive from this corona.

Parma Corona: Parma Corona is bounded by a topographic rim and a fracture ring, both of which extend about half way around the structure. The relations of corona structures with flows from Bayara Vallis are mixed; to the south, Bayara flows are clearly superposed on corona structures, including fractures of the concentric ring. To the north, however, some more distal concentric structures related to Parma cut Bayara flows. Thus the corona structures and the vallis flows overlap in time. Derived flows are limited to the corona interior; they do not appear to be cut by any corona structures.

Sulis Corona: Sulis Corona is an almost perfect doughnut shape; its outer edge is delineated by a narrow but complete fracture ring, inside of which is a complete topographic rim. The elevated rim is characterized by approximately evenly spaced, radiating wrinkle ridges. Flows occur only to the east of the corona, where they are moderately abundant. Concentric corona structures cut these flows, as do the ridges in the belt connecting Sulis with Parma Corona. Flows from Bayara Vallis are superposed on Sulis flows.

Vasudhara Corona: A wide concentric fracture ring bounds Vasudhara Corona for about half of its circumference, but the corona lacks a topographic rim that is higher than surrounding terrain. Flows occur mostly west and southwest of the corona. These flows are cut by concentric corona fractures. An extensive shield flow is superposed on Vasudhara flows and also sharply truncates both concentric and radial fractures related to the corona.

Corona b: No flows are associated with corona b, and the bounding fracture ring is narrow, incomplete, and not altogether convincing. However, a complete topographic rim surrounds the depressed center, forming a doughnut shape similar to that of Sulis Corona. Thus corona b qualifies as a stealth corona (Tapper, 1997; Stofan and others, 2001). This topographic rim appears to consist of regional plains material. Distal structures of Aušrā Dorsa cut corona b.

Corona c: This feature is an irregular, elongate structure having a depressed center but only a partial and poorly developed bounding fracture ring and no topographic rim. Flows are moderately extensive. Structures apparently related to the corona cut these flows, but because corona c lies within a more extensive belt of ridges and fractures structures actually associated with the corona are not apparent. This structure is best categorized as “coronalike” because the structures and topography generally considered diagnostic of a corona are not well developed.

Sand Corona: Sand Corona is similar to Sulis Corona in being bounded by a narrow fracture ring that, unlike the ring for Sulis, is not complete. Inside this narrow ring is a complete topographic rim having approximately evenly spaced, radiating wrinkle ridges. This rim consists of elevated regional plains material. The central depression of Sand Corona is very irregular (fig. 5) rather than being nearly circular as is the central depression of Sulis Corona. Sand Corona lies in a well-developed belt of complex wrinkle ridges that connects Trotula and Sand Coronae to the northwestern twin of Nana-Buluku Coronae. Flows are not extensive and are mapped only east of the corona. These flows are cut by the wrinkle ridges connecting Sand and Trotula Coronae.

Trotula Corona: Trotula Corona has an interesting shape. The broad, nearly complete fracture ring defines a teardrop shape, whereas the smaller, complete topographic rim, which lies inside of the fracture ring, is circular. The topographic rim is characterized by approximately evenly spaced radiating wrinkle ridges, similar to what is present at Sulis and Sand Coronae. Flows are sparse and limited to the depressed center of the structure. Corona structures do not cut these flows, but the flows do not appear to be superposed on any structures either.

Simoting Corona: Simoting is a true stealth corona; it is defined entirely by a topographic rim and has a belt of fractures only along about half of its west side. Despite its large size, this structure was not discovered by those who named the nearby features of comparable or somewhat smaller dimensions. The topographic rim is characterized by approximately evenly spaced radiating wrinkle ridges, like those present at Sulis, Sand, and Trotula Coronae. In stereo, this structure looks like a rubber life raft! The topographic rim appears to consist of regional plains material. Simoting Corona possibly should be considered part of Trotula Corona, which then would become a twin or multiple structure. It is named and described separately because it is structurally unlike Trotula.

Kostroma Coronae: These structures form twin or multiple coronae, consisting of two connected parts, the total being elongate in a west-northwest direction. The southeast twin is almost completely surrounded by a broad fracture ring; the northwest twin is bounded by a narrow and incomplete fracture ring but also by a complete topographic rim (fig. 6). Flows are extensive, and the older ones are cut by concentric corona fractures. The terrain northeast of the coronae is relatively low, and at least the youngest lavas from Kostroma Coronae have flowed down the slope into this low area, superposing on regional plains material.

Nana-Buluku Coronae: Nana-Buluku Coronae are twin or multiple coronae similar in appearance, orientation, and size to Kostroma Coronae. Both twins have fracture rings and topographic rims. For the northwest twin, the fracture ring lies inside the topographic rim; for the southeast twin, the two boundaries coincide. Flows are limited in extent and appear to be cut by concentric corona structures.

Yaroslavna Corona: This corona is an irregular structure having two concentric topographic rims. The outer rim is narrow and coincides with the incomplete fracture ring; the inner rim is broader and immediately surrounds the central depression. Three flows, each having a different morphology, emanate from Yaroslavna. To the west is a digitate flow with morphology typical of most flows on Venus; to the north is a stubby lobe-shaped flow with a hummocky surface; and to the southeast is a stubby lobe-shaped flow with a smooth surface. These stubby flows may consist of lavas more evolved than the basalt inferred to make up most flows on Venus. Concentric Yaroslavna structures cut all three of these flows, but the lobe-shaped flows appear younger than many structures on the surrounding plains and younger than the digitate flow.

Corona d: Corona d lies close to and north of Cavell Corona but was not recognized by those who named adjacent structures because it is essentially a stealth structure. It is defined primarily by a horseshoe-shaped topographic rim that is open to the south, toward Cavell. Flows from Cavell Corona are apparently continuous across the topographic rim of corona d, which suggests that this corona is younger than the volcanism associated with Cavell Corona. Where not surfaced by flows from Cavell, the topographic rim of corona d consists of elevated regional plains material.

Cavell Corona: Cavell Corona is a well-defined structure having a wide and complete fracture ring coincident with a complete topographic rim, and a deep central depression. Flows are extensive and, as discussed above, appear to be older than the topographic rim of corona d. Concentric and radial structures from Cavell cut Cavell flows.

Xquiq Corona: Concentric ring fractures wrap around the west, south, and east sides of this corona and then taper northward toward Nana-Buluku Coronae to form an overall teardrop pattern. Where the fracture ring tapers northward the northern boundary of Xquiq is defined by a short segment of topographic rim, such that the central depression is a more normal oval shape. Flows are extremely limited and are cut by the ring fractures.

Corona e: Corona e has no topographic rim and a very narrow and poorly developed fracture ring. The only significant topography associated with the structure is a central mound, rather than a central depression. No flows associated with this corona have been identified.

Dzuzdi Corona: The central part of Dzuzdi is a well-formed doughnut shape, with a complete topographic rim circling the central depression. External to the topographic rim is a broad but incomplete fracture ring that circles about half of the corona. Dzuzdi Corona is in a belt of complex wrinkle ridges that links corona f, Bécuma Mons, Dzuzdi Corona, and Cavell Corona. Structures in this belt deform corona Dzuzdi. No associated flows have been found.

Ilmatar Corona: Ilmatar Corona is bounded by a broad, complete fracture ring that coincides with a nearly complete topographic rim. Flows are limited. To the south a small area of Ilmatar Corona flow material (unit fcI) is cut by a corona concentric structure; to the north is a stubby lobate flow that is superposed on fractures of the corona ring. The stubby flow may consist of a more evolved magma, similar to those associated with Yaroslavna Corona. The floor of the corona hosts a dense array of wrinkle ridges that have an orientation not quite parallel to the wrinkle ridges external to the corona.

Ponmakya Corona: Ponmakya Corona has a ring of fractures only around its northern part where a partial topographic rim also may be present. The center of the corona is completely flooded with volcanic material, and the southern boundary of the structure is inferred to be near the northern limit of a strong array of radial fractures that is present south of the flooded interior of the corona. Flows from this corona also cover extensive areas north and south of its flooded interior. Shield flows are superposed on radial structures of Ponmakya.

Modron Corona: Modron Corona is a small and almost perfectly circular structure defined by a broad and nearly complete fracture ring that is coincident with a nearly complete topographic rim. The only gap is a small one to the north through which younger shield flows have penetrated the interior of the corona, superposing ring fractures. A small flow field east of the structure is probably derived from this corona.

Corona f: Corona f is an unusual structure that is primarily bounded by a low, discontinuous topographic rim that defines a large horseshoe pattern, open to the north. This ridge extends all the way north to Bécuma Mons, and it crosses Modron Corona as well. The crater Edgeworth is entirely within the structure. South of the topographic rim is a smaller horseshoe pattern defined by fractures. Thus this structure may be a twin corona or coronalike feature. Flows are not very extensive, and at least some are cut by corona structures.

Corona g: This corona is a very subtle feature having a poorly developed fracture ring and no topographic rim. The interior topography is complex with both elevated and depressed regions, none of which exhibit much relief. Flows are moderately abundant. Corona g structures cut its flows. This feature is probably best categorized as a coronalike structure.

Beyla Corona: The largest corona in the quadrangle, Beyla has an associated fracture pattern that reminds one of a trilobite. An outer fracture ring defines the structure. This ring is broad and very well developed in the northern part of the corona, much narrower and less obvious to the south. In the northern part of the corona a second broad fracture ring lies within the main ring. Also in the northern part of the corona a partial topographic rim is present just inside the outer fracture ring. The central depression appears to be deeper in the north than in the south, and a large elevated area occurs in the center (see Squyres and others, 1992a, fig. 11b). Coincident with the central elevation is a strong fabric of north-south fractures that have the same trend but are not continuous with radial structures extending northward from the corona. Flows are limited, and those that are present are cut by concentric corona structures. Some corona fractures also cut crater Kafutchi, which is on the central elevated area within the corona.

Kumang Corona: Kumang Corona is the smallest corona in the quadrangle. It is bounded on both east and west sides by partial fracture rings and coincident topographic rims. The interior is flooded by flows from the corona. This corona is the focus of spectacular fans of grabens both north and south of the corona. These grabens cut regional plains, but they cut only the periphery of the corona flows in the central part of the structure. However, structures of the incomplete fracture ring cut these corona flows.

TESSERA STRUCTURES

Structures deforming tessera material are of three general types: grabens, broad ridges, and narrow, bright lineaments of uncertain genesis. Grabens cutting tessera material are common and can range in width from the limit of recognition resolution (a few hundred meters) to as much as 10 km. Grabens in any given exposure of tessera have one or at most two orientations, but tessera graben trends over the entire quadrangle exhibit no consistent pattern. Many grabens are flooded by surrounding plains or other volcanic materials. The bright lineaments are spaced from less than 1 to 2 or 3 km apart and, like the grabens, are generally confined to one or two orientations within any single tessera exposure but are not characterized by common trends quadrangle-wide. Commonly these lineaments are so closely spaced that they represent a penetrative fabric at SAR resolution. This fabric effectively masks the original characteristics of tessera material and causes the backscatter and root-mean-square (rms) slope to be very high (table 1). Ridges are relatively rare and when present commonly trend about parallel to the narrow bright lineaments. All of these structures are sharply truncated at contacts between tessera and surrounding units.

FRACTURES, FAULTS, AND LINEAMENTS

As was true for the Sappho Patera quadrangle (McGill, 2000), plains materials in the Bereghinya Planitia quadrangle are cut by a fabric of narrow radar-bright lineaments that have no obvious association with any other structural or topographic feature. Individual lineaments range in length from a few to more than 100 km. Over much of the quadrangle, this fabric cannot be separated from the complex lineament patterns associated with coronae and deformation belts. However, in the southern part, where these complexities are not present, the lineaments define a fabric trending between north-south and north-northeast. The lineaments are inferred to be extensional fractures based on local evidence of graben geometry for some of them. Locally relative ages of structures deforming plains materials can be determined; this fabric appears to be consistently older than both radial graben sets and wrinkle ridges.

Four features within the Bereghinya Planitia quadrangle are included in a global catalog of graben swarms that could be due to the presence of radially propagated dikes that did not reach the surface (Grosfils and Head, 1994; E.B. Grosfils, written commun., 2001). The four sources listed are Ba'het Corona, Audhumla Corona, Ponmakya Corona, and Bécuma Mons. The most pronounced radial structures associated with Ba'het Corona are those in the structural bundle connecting Ba'het and Onatah Coronae. These could, of course, overlie buried dikes, but the pattern is not really radial in the sense that the individual structural elements do not diverge from each other with distance from the presumed source. Audhumla Corona does not have a well-defined radial pattern at all. Most clearly associated lineaments and grabens are concentric rather than radial, and those that are more nearly radial probably relate more to Sigrun Fossae than they do to Audhumla Corona. Bécuma Mons is the center for a spectacular set of radial grabens, which could be due to radial dikes. Ponmakya Corona also has well-defined grabens radiating from its center, most of which occur to the north and south. Two other possible centers of radiating dikes in the quadrangle are much smaller than the four proposed by Grosfils and thus easily missed in a global search using lower resolution images. The first of these is the area of low-relief shield plains material (unit psl) centered just south of the southern border of the quadrangle at about 6° E.; the other is Kumang Corona, centered at 25° N., 11.8° E. Individual grabens in these two swarms are up to 150 km long. Those related to the low-relief shield plains are curved so that they approach being a parallel set with distance from the source, and they approach being parallel to the pervasive lineament fabric discussed above. Close to the source, however, the grabens are younger than the pervasive lineament fabric because locally they break up into en echelon segments that individually parallel the older fabric but which overall define the trend of the younger graben. The grabens from Kumang Corona fan with little curvature of individual structures.

WRINKLE RIDGES

As is true for most plains areas on Venus, wrinkle ridges are nearly ubiquitous in the Bereghinya Planitia quadrangle. Although local patterns are present (such as the arachnoid pattern described earlier), the quadrangle as a whole has no consistent wrinkle-ridge pattern because of the complexities introduced by deformation belts, corona structures, and the structures in the belts connecting the coronae into chains. In the south-central and southeastern parts of the quadrangle, where deformation belts are not present and coronae are rare, wrinkle ridges appear to be similar to those found in plains areas elsewhere. In the south, one persistent orientation is within a few degrees of east-west. This orientation is a continuation of the pattern in the northern part of the Sappho Patera quadrangle (McGill, 2000). Other trends also are present, such that two sets of wrinkle ridges are present at any given locality. The other trends differ from place to place, however. Wrinkle ridges in the southwestern part of the quadrangle exhibit a strong north-south trend, and wrinkle ridges trending northwest and northeast are present in various places between coronae and their linking belts. Most of the individual wrinkle ridges are typical, being long, sinuous, and very narrow (order of resolution limit). Some are wider and double, comparable to the braided wrinkle ridges in the corona chains discussed above. At one locality (46° N., 24° E.), wrinkle ridges clearly include a broader ridge on which the typical narrow, bright ridges occur (fig. 7). This geometry is unlike most wrinkle ridges on Venus, which generally do not include the broader ridge, but very similar to the geometry of lunar and martian wrinkle ridges (Maxwell and others, 1975; Watters, 1988). The absence of broader ridges may be only apparent due to flank slopes too gentle to yield resolvable differences in radar backscatter. Wrinkle ridges are present on every plains and flow unit in the quadrangle but are less abundant on young materials, such as Onatah and valles flows, than they are on regional plains material and other corona flows. Thus the formation of wrinkle ridges must have continued throughout the interval during which many of the material units were emplaced.

DISCUSSION

The structural and chronological observations derived from geologic mapping in the Bereghinya Planitia quadrangle bear on some important tectonic issues of global interest. These issues include the ages of structures and material units relative to different sets of wrinkle ridges, the ages of corona flows and structures relative to regional plains material, the sequence of development of coronae, and the relation between stratigraphic age and apparent degradation of impact craters.

Commonly, a regionally dominant, older set of wrinkle ridges is present on Venus against which members of younger sets terminate in "T" intersections. In a large area of plains, including the plains in the Sappho Patera quadrangle (McGill, 1993), the dominant, and oldest, set trends roughly east-west. This pattern is also present where the plains materials of Bereghinya Planitia are not deformed by abundant coronae and the structural belts connecting coronae. This relatively simple situation is present in the northern part of the Sappho Patera quadrangle (McGill, 2000) but is limited to a small area in the south-central and southeastern part of the Bereghinya Planitia quadrangle; elsewhere, other structural complexities either mask the regional age pattern of wrinkle ridge ages or they actually destroy this age pattern.

On a global scale, coronae show remarkable variability in morphology, evolutionary sequence, age relative to regional plains material, and volume of associated volcanic material (Stofan and others, 1992, 1997; Squyres and others, 1992a; Copp and others, 1998). The coronae and coronalike features in the Bereghinya Planitia quadrangle include many of the morphologic types defined by Stofan and others (1997). They also vary significantly in the volume of associated flows, ranging from no associated flows to large flow fields; flows from Onatah Corona, for example, cover several percent of the area of the quadrangle. For most of the coronae, concentric and radial structures cut the associated flows, and thus most of the coronae in this quadrangle seem to share a common evolution from early volcanism to late structural disruption. In support of this relationship is the superposition of structures in the belts connecting coronae on corona flows. A possible exception to this consistent early volcanism is the stubby lobate flow associated with Ilmatar Corona, which appears superposed on the fracture ring defining the corona. This stubby flow may consist of magma more evolved than basalt, which would be consistent with both its morphology and its relative age. In addition, three coronae (Trotula, Damona, and Parma) have flows confined to their floors that are not cut by any corona structures. However, it is not clear if the flows are younger than the structures or if the central parts of the coronae have no structures.

Of major concern are the ages of corona flows and corona structures relative to regional plains material. Most corona structures are younger than regional plains material, although for a few coronae some structures cut bright plains material and are truncated by regional plains material, whereas other structures related to the same coronae cut regional plains material. This implies that the structures associated with some coronae began to develop before emplacement of the adjacent regional plains material but continued to form after emplacement of regional plains material. For most coronae, however, all deformation appears to post-date regional plains material. Relative ages of regional plains material and corona flows are not everywhere clear. Those corona flow fields that include sharply defined, radar-bright digitate flows provide good evidence that at least these bright flows are younger than regional plains material. However, most corona volcanics have more subtle flow forms and radar backscatter values similar to regional plains material, and locally the contacts between these volcanics and regional plains material appear to be gradational or uncertain. Good examples of uncertain contacts are on the east side of Beyla Corona and on the west side of Vasudhara Corona. The density of wrinkle ridges on corona flows and on regional plains material is similar, with the exception of flows from Onatah Corona, which have a lower density of superposed wrinkle ridges. Some of the material mapped as regional plains material likely was derived from coronae, and thus most corona flow materials are probably the same age as or younger than regional plains material.

Stofan and others (1997) describe three groups of coronae based on geologic setting: rise coronae, isolated coronae, and chasmata coronae. The coronae of Bereghinya Planitia are not on a rise nor on a chasma, but most of them are clustered together so the term "isolated" seems inappropriate for all of them except Beyla and Kumang. Furthermore, the sequence of volcanism and fracturing noted for most Bereghinya Planitia coronae, as well as the dominant morphologies, seem to fit the description of chasmata coronae better than the description of isolated coronae. Corona fractures and ridges for most coronae in Bereghinya Planitia deform regional plains material, whereas Stofan and others (1997) maintain that isolated coronae are generally embayed by plains volcanism. The coronae in this quadrangle are embayed by shield and valles flows but generally not by the areally dominant regional plains material, except that some coronae provide evidence of progressive deformation with some fractures embayed by regional plains material, others from the same coronae cutting regional plains material.

Most of the impact craters in the Bereghinya Planitia quadrangle are young relative to other structures. Kauffman is younger than Aušrā Dorsa, Kemble is both older and younger than Sigrun Fossae structures, and Elenora is younger than flows from Onatah Corona, which in turn are younger than Sigrun Fossae and Audhumla Corona. Prichard, Lena, Ayisatu, Noreen, Edgeworth, Browning, Melanka, and Mona Lisa are all superposed on wrinkle ridges, including the closely spaced ridges in the belts connecting coronae to each other. However, Stina is older than northwest-trending wrinkle ridges, and Ariadne yields a self-contradictory relation with east-west wrinkle ridges; the crater ejecta are superposed on these wrinkle ridges, but the digitate crater flow south of Ariadne may be cut by east-west wrinkle ridges (this relation is uncertain because a possible interpretation is that the crater flow found gaps and en echelon offsets in the wrinkle ridges and thus simply flowed around them). Chubado, which is younger than structures parallel to the trend of the elevated belt connecting Audhumla and Ba'het Coronae, is cut by faults transverse to the belt. These transverse faults are grabens radial to Kostroma Coronae. Kafutchi is cut by north-south-trending lineaments in the interior of Beyla Corona.

All of the craters in the quadrangle except Kafutchi, Chubado, and Mona Lisa have what appear to be fresh ejecta, and many have associated dark halos or parabolas (table 2). If post-impact volcanism degraded craters by burying halos, parabolas, and secondary craters and by embaying ejecta and flooding the floors, as has been suggested (Herrick and Sharpton, 2000), then one would expect indications of relative youth, such as secondary crater fields, halos, and parabolas, to be preferentially associated with craters having floors that are not flooded; that is, bright floors. Four craters have secondary crater fields (Lena, Mukhina, Browning, and Ferber); three of these have floors of intermediate backscatter, one has a dark floor. Edgeworth and Noreen appear to be co-sources for a combination parabola and streak band. Noreen has a bright floor, but Edgeworth has a dark floor. Overall, ten craters have associated halos or parabolas. Of these, two have bright floors, five have floors of intermediate backscatter, two have dark floors, and one (Elenora) is too small to measure floor backscatter. Where relations are clear, impact craters are mostly younger than wrinkle ridges. Only one crater, Stina, is unambiguously older than wrinkle ridges and it has a bright floor. Thus no evidence exists in this quadrangle for a correlation between crater floor brightness and apparent age or degradation of the crater.

GEOLOGIC HISTORY

The chronology of events and materials within the Bereghinya Planitia quadrangle is tied to the areally dominant material unit, regional plains material. This unit consists primarily of plains material, presumably volcanic, that cannot be linked to a specific source such as a corona, a caldera or dome, or a vallis. Regional plains material varies in radar backscatter and texture, but consistently mapping subdivisions based on these variations is not possible. Determining how many years were required to emplace regional plains material is not possible, nor is it possible to estimate the time required to emplace this unit relative to the time spans involved in emplacing all other units in the quadrangle. The absence of relative age control is a direct result of the sparse impact crater record, which results in the inability to separate material units in time by means of statistically significant differences in crater frequency (Campbell, 1999).

The oldest materials in the quadrangle occur as two mapped units: tessera and bright plains materials. Both occur as inliers within regional plains material, and both are clearly older than regional plains material because structures present in the inliers are sharply truncated by regional plains material at their contacts. Tessera material is cut by at least two trends of structures and by large grabens that commonly are flooded by regional plains material. Bright plains material is cut by only one trend of structures and no large grabens. Both types of inliers are scattered throughout the quadrangle, and thus the differences in deformation are likely due to age differences rather than areal differences in deformation history. Thus tessera material is the oldest material in the quadrangle, and bright plains material the next oldest. No impact craters superpose tessera and bright plains materials, and no other means exists to determine relative ages between isolated inliers. Thus determining whether either of these materials is of similar age throughout the quadrangle is not possible, nor is it possible to estimate the elapsed time between emplacement of tessera material and emplacement of bright plains material. In places, bright plains material is difficult to distinguish from regional plains material that is intensely deformed by closely spaced fractures. Thus bright plains material simply may be remnants of early plains material covered by later flows included in regional plains.

The small, unnamed ridge belt centered at 46.5° N., 26° E. appears to be embayed by regional plains material. Most or all of the belt consists of bright plains material, consistent with the pre-regional plains material age implied by the embayment relation. Ridge belts on Venus have generally been interpreted as due to compressive stresses oriented normal to their trends (Barsukov and others, 1986; Banerdt and Golombek, 1988; Zuber, 1990; Solomon and others, 1992; Squyres and others, 1992b). Thus this small ridge belt implies an east-northeast–west-southwest orientation of maximum compression at some time before emplacement of the regional plains material.

The larger areas of bright plains material generally occur on low, gentle hills within the plains, with regional plains material superposed on bright plains material around the periphery of the hills. The gentle slope angles on these hills imply that regional plains material is thin, at least near these exposures of bright plains material. If it is thin throughout the quadrangle, then the absence of partially buried impact craters cannot be due to burial by regional plains material—some other event must have occurred that destroyed older craters. The emplacement of regional plains material records a major volcanic event in the history of Venus, and this is true whether this event required a geologically brief interval (millions or tens of millions of years) or a lengthier interval (hundreds of millions of years).

Structures making up the deformation belts Sigrun Fossae and Aušrā Dorsa cut regional plains material, and thus these belts are at least in part younger than the emplacement of regional plains material. However, Sigrun Fossae structures also cut bright plains material, and some of these structures may be older than regional plains material. Although the lineaments associated with Aušrā Dorsa cut regional plains material, the dorsa ridges may be older; the evidence is equivocal. Flows from Belisama Vallis are partially controlled by ridges in Aušrā Dorsa, and flows from Bayara Vallis are superposed on structures of Sigrun Fossae. Thus these belts must be at least in part older than the valles flows. Flows from Onatah Corona also truncate peripheral structures of Sigrun Fossae.

The plains that form most of Bereghinya Planitia consist of several material units, including regional plains material, low-relief shield plains material, dark plains material, corona flows, shield flows, flows from Gula Mons, and valles flows. Some of these units are consistently older or consistently younger than regional plains material; others suggest a more complex history with several types of volcanic sources operating simultaneously.

Shield flows occur in numerous patches throughout the quadrangle. Superposition and truncation relations indicate that some of these patches are older than regional plains material, some younger, and some probably essentially the same age. Material derived from low-relief shields is superposed on regional plains material, but in places the contacts are gradational, suggesting that low relief shield plains material is partly younger and partly the same age as material of regional plains. Dark plains material embays adjacent regional plains and thus must be at least locally younger. Flows from valles and from Gula Mons are entirely younger than regional plains material. Homogeneous plains material is probably younger than regional plains material, based on local control of contacts of homogeneous plains material by wrinkle ridges that deform regional plains material.

Relative ages of corona flows and regional plains material are not consistent. Many contacts between corona flows and regional plains material are gradational, implying a similar age. Locally, vague flow forms occur within regional plains material, and these flow materials may be corona derived. However, some corona flows are clearly superposed on regional plains material; examples include the radar-bright flows derived from Kostroma Coronae, corona f, and Cavell Corona, and all flows from

Onatah Corona. Thus corona volcanism is inferred to overlap extensively with emplacement of regional plains material; some volcanism is the same age as regional plains material, some younger.

Cutting the regional plains in the Sappho Patera quadrangle (McGill, 2000) are pervasive fabrics of narrow, radar bright lineaments that are not obviously associated with any structural or topographic feature. One of these fabrics trends north-northeast, and this fabric is present with a north-northeast to north-south orientation on the plains in the southern part of the Bereghinya Planitia quadrangle. Farther north, this fabric is essentially lost amidst all the structural complexities that characterize most of the quadrangle. Some of the individual lineaments making up this fabric are resolvable as grabens, and thus this fabric implies that the earliest deformation to affect regional plains material was extensional with maximum stretching oriented roughly east-west. In addition to regional plains material, this fabric cuts shield flows and low-relief shield plains material; the fabric does not appear to be present on homogeneous plains material, dark plains material, valles flows, and flows from Onatah Corona, suggesting that the fabric is older than these units. Gula flows partially fill grabens that are part of this early fabric. The Gula flows are thus demonstrably younger than the early extensional event. Unfortunately, the pervasive structures associated with coronae preclude determining if this fabric exists on most corona flows.

All of these materials, including Onatah and valles flows, are deformed by wrinkle ridges. In this part of Venus, the earliest wrinkle ridges trend roughly east-west (McGill, 1993, 2000), later ones have other orientations. This also is true for the southernmost part of the Bereghinya Planitia quadrangle, but the sequence elsewhere in the quadrangle is masked by younger structures. Some of the youngest materials, such as flows from Onatah Corona, appear to have fewer superposed wrinkle ridges than does regional plains material. Furthermore, some of the radar-bright digitate flows from coronae apparently are not deformed by wrinkle ridges, but this is somewhat ambiguous because wrinkle ridges are very difficult to resolve on a unit that has the same high backscatter value. Also, the emplacement of dark plains and homogeneous plains materials likely did not begin until after wrinkle ridges began to form.

Most structures related to individual coronae are younger than regional plains material and younger than flows from each corona, but older than most flows derived from shield fields and valles. Structures within the complex belts connecting coronae are younger than regional plains material. These belt structures also are younger than most corona flows, but they are older than flows from Onatah Corona, some of the bright digitate corona flows, and the stubby, lobate flows associated with Yaroslavna and Ilmatar Coronae. The belts connecting coronae consist of bundles of closely spaced wrinkle ridges, commonly astride a low ridge. This relation implies contraction normal to the belts, resulting in a seemingly chaotic stress and strain field because the belts have many different trends, and they connect coronae that generally are associated with extensional structures.

All 24 impact craters and all 6 impact splotches are younger than regional plains material. One crater is clearly younger than a young corona flow (Onatah), two are clearly older than corona fractures (Beyla, Kostroma), and two are younger than the deformation belts. About half of the craters are younger than wrinkle ridges, but one appears to be older than wrinkle ridges. The ages of the others relative to wrinkle ridges are unknown.

Several chronological observations are of more than local interest.

1. If one were to map a “plains with wrinkle ridges” unit, as some have done (Basilevsky and Head, 2000), then virtually all plains and flow units would be incorporated into this unit. What is clear from mapping this quadrangle is that the deformation responsible for wrinkle ridges occurred after emplacement of most material units, except for at least some impact craters. The lesser density of wrinkle ridges on the youngest units also implies that the deformation responsible for wrinkle ridges was progressive.

2. In some localities on Venus flows associated with clusters of small edifices, the shield fields of Aubele and others (1992), form a mappable unit that appears to be older than adjacent regional plains material (Basilevsky and Head, 2000; Bridges and McGill, 2003). This has led to the proposal that the volcanic style of Venus evolved through time from volcanics derived from many small edifices, through plains flood volcanism, to volcanics derived from a few large central volcanoes (Basilevsky and Head, 1998, 2000). The stratigraphy within the Bereghinya Planitia quadrangle does not support this concept because many volcanics associated with clusters of small edifices are clearly younger than regional plains material, a result that is in general agreement with results reported by Guest and Stofan (1999) and Addington (2001) from more global studies.

3. Inferring that horizontal principal stresses can be derived in a simple manner from trends of extensional and contractional structures leads to an almost chaotic pattern of stresses in this quadrangle. The earliest structures deforming regional plains material, roughly north-south fractures and east-west wrinkle ridges, are consistent with each other and suggest a pattern of north-south compression and east-west tension that probably affected the shallow crust over the entire quadrangle. However, the deformation belts, the belts connecting coronae, and the coronae themselves cannot be explained by a simple and areally extensive pattern of principal stresses. Some of this chaos could be mitigated if much of the trend variability

is temporal rather than spatial, but for these major structures age differences cannot be resolved, if in fact they exist. Corona formation is generally related to the rise of thermal plumes (Squyres and others, 1992a; Smrekar and Stofan, 1997) followed by lateral flow of plume material and eventual downwelling after cooling. The large number of coronae in Bereghinya Planitia would suggest a swarm of plumes, and if these were active at the same time, or overlapped significantly in time, it is possible to envisage centers of uplift and extension that became coronae surrounded by zones of competing flow from several plumes that resulted in a complex pattern of compressive principal stresses. Why there should be so many plumes in this relatively small area is not known.

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