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THE VENUS GEOLOGIC MAPPERS' HANDBOOK

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INTRODUCTION

Radar-image data recently acquired by the Magellan spacecraft now make possible an exciting new venture: the geologic mapping of the planet Venus. Such mapping will form a basis for determining the planet's geologic history and understanding its modifying processes. To fulfill these goals, the Venus Geologic Mapping (VMAP) program has been instituted to provide systematic scientific investigations of map quadrangles that will result in a global set of published geologic maps. VMAP, sponsored by NASA's Venus Data Analysis Program (VDAP), is the most ambitious mapping program in terms of size and complexity yet attempted by planetary geologists.

The VMAP program is made possible by the global radar-image database gathered by the Magellan spacecraft, which was launched from Kennedy Space Center in Florida on May 4, 1989. On August 10, 1990, Magellan entered orbit around Venus and acquired the first radar images 6 days later. The radar is virtually unaffected by the thick Venusian atmosphere, and the radar images have a higher resolution (120-360 m) than has been achieved by Earth-based or other spacecraft missions. In mapping Venus, Magellan has revealed unparalleled details of mountain ranges, high plateaus, volcanoes, vast volcanic plains and lava flows, and areas of extensively deformed crust.

The map series consists of 62 quadrangles at 1:5,000,000 scale to be published in the Miscellaneous Investigations Map Series of the U.S. Geological Survey (USGS) (fig. 1). This project is being administered by NASA Headquarters and coordinated by the USGS Branch of Astrogeology (Appendix A). Initial map proposals in 1992 were reviewed by the VDAP review panel; subsequent new proposals have been reviewed by the Lunar and Planetary Geology Review Panel. Mapping progress, workshop organization, and science issues are overseen by the VMAP Steering Group. USGS staff are responsible for base–map production and distribution, map editing, geographic name assignments, and geologic map production.

The basic product of the VMAP program, the 1:5,000,000–scale geologic quadrangle, is meant to provide a meaningful description of the geology of an area, which, in turn, will support various interpretive topical studies. Adherence to established mapping principles should preserve the value of the map despite the inevitable progress in geologic interpretation. Of course, such principles can be applied through various creative approaches. Geologic mapping is no mere mechanical exercise, because it requires interpretation of geologic data.

This handbook has been produced to assist geologic mappers in the VMAP program to meet the following challenges: (1) to gain an understanding of the nature and complexities of the Magellan radar dataset and its bearing on the interpretation of geologic terrain, so as to avoid a myriad of potential pitfalls; (2) to facilitate the application to Venus of both conventional and special planetary mapping techniques; and (3) to promote usage of USGS guidelines for map publication. To first order, geologic mappers will employ standard photogeologic techniques on SAR backscatter mosaics; refinements may result from analysis of various available radar datasets. Mappers will no doubt encounter specific mapping problems not addressed herein that will require their own creativity and judgment to resolve (at times with assistance from others engaged in geologic studies of Venus).

In addition to this handbook, geologic mappers should also have for reference the Magellan data handbooks by Ford and others (1989) and Michaels (1992), the special issues of *JGR–Planets*, "Magellan at Venus" (1992, v. 97, nos. E8 and E10), and "Suggestions to Authors of the Reports of the United States Geological Survey," edited by Hansen (1991). These publications will provide supplementary technical information, illustrative figures, and style guidelines that will assist in understanding Magellan radar data and in producing geologic maps of Venus. Other relevant publications are offered in our "Recommended Reading" list.

We anticipate that mapping techniques and guidelines will evolve, making some of the discussions in this handbook obsolete or deficient. We will appreciate suggestions for updates and additions to be included in future versions.

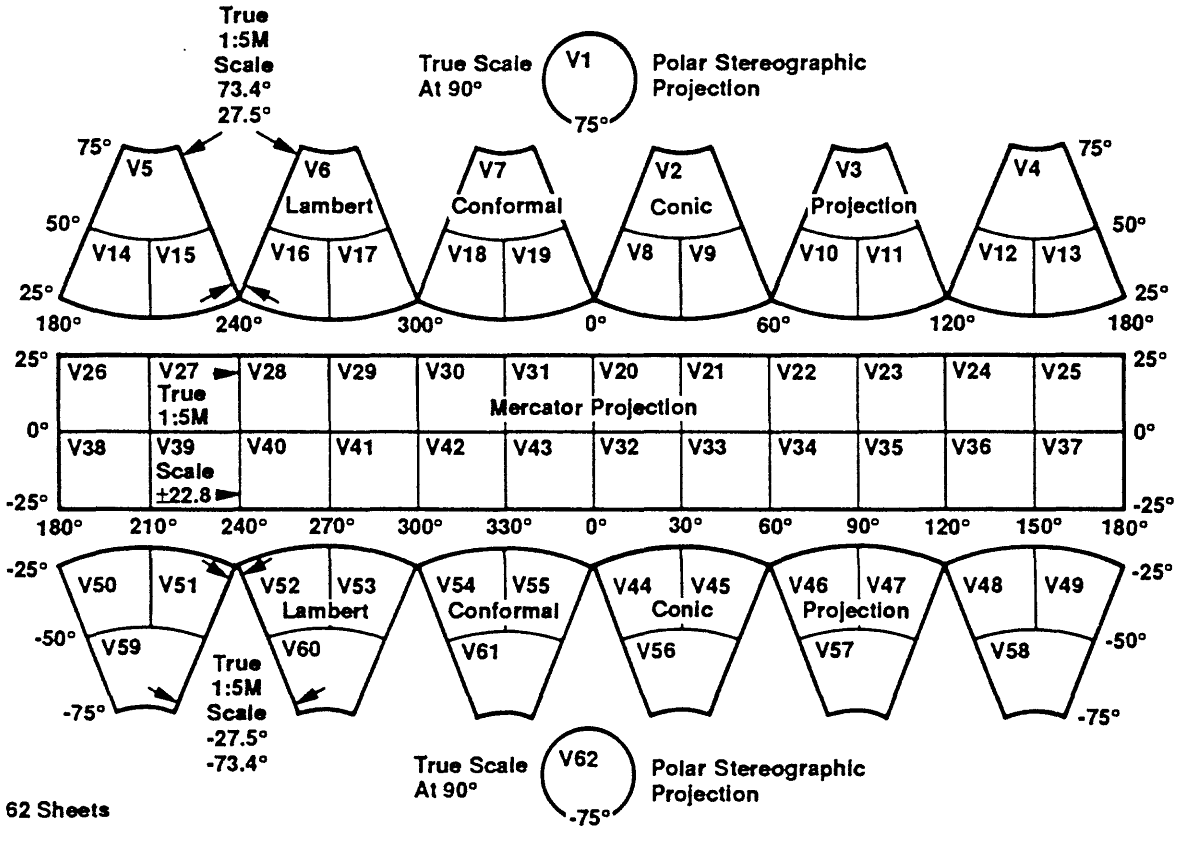

Figure 1. Index of 1:5,000,000-scale quadrangles of Venus; see text for further explanation. Reprinted from Ford and others (1989, figure 11).

OVERVIEW OF DATA SOURCES

Mission Summary

Magellan's global dataset of Venus has been acquired as part of a series of spacecraft investigations of the inner planets (Mercury, Venus, Earth, and Mars). The Magellan data are more complete than similar data for Earth (whose largely unmapped ocean floors make up 70 percent of its surface). However, the Magellan data—images and measurements of the physical and electrical properties of the surface of Venus, were acquired at the radio wavelength of 12.6 cm, very different from data of primarily optical wavelengths that previously have been acquired for planetary geologic mapping. The properties of the surface that influence the reflection of radio waves are not the same as those that determine the optical reflection properties. This critical factor must be considered when compiling geologic maps based on synthetic aperture radar (SAR) images and surface properties measured at radio wavelengths.

In this section we discuss (1) how the Magellan mission was carried out, (2) the function of the radar instruments, (3) how the data were acquired and processed, and (4) what finished data products are or will become available. For detailed information, please see the Recommended Reading.

The Magellan radar mapping mission to Venus has provided SAR imaging covering 98.3% of the planet's surface plus topography, surface slope, radar reflectivity, and radio thermal-emissivity datasets covering similar percentages of the surface (Saunders and others, 1992). The imaging and ancillary datasets are the resource materials for the VMAP program.

The Magellan spacecraft went into orbit around Venus with an orbit period of 3 hr. 16 min. and inclination of 85°. This corresponds to approximately 8 orbits per day and a total of 1,760 orbits during one 243-day rotation period (a 'cycle' in Magellan parlance). Periapsis of the orbit was at lat 10° N. and the direction of motion as the spacecraft passes through periapsis is from north to south. The altitude of the spacecraft at periapsis was 294 km and the eccentricity of the orbit was such that its altitude over the north pole was 2,100 km. The 85° inclination angle for the orbit was chosen to allow the SAR to image the polar regions.

The first four weeks of the mission after orbit insertion were devoted to engineering tests, but some test data were acquired as well. Systematic data collection began on September 15, 1990. Coverage by cycle 1 was completed on 15 May, 1991, and cycle 2 coverage was completed on 14 January, 1992. Cycle 3, the last cycle for which systematic SAR data were obtained, ended on 14 September, 1992. Cycle 4 mission operations have focused on the collection of high–resolution gravity data. Continuation of the Magellan mission beyond cycle 4 involves aerobraking the spacecraft into a low–altitude (250 km) circular orbit that will permit the acquisition of improved gravity data.

Left-looking SAR imagery (i.e., imagery with the 3.7-m SAR antenna looking to the left (to the east) of the orbit plane), covering 83.7% of the planet's surface, was obtained during cycle 1 (see Michaels, 1992, fig. 2); 54.5% was covered in cycle 2 with a combination of left- and right-looking imagery (Michaels, 1992, fig. 3); and 22.8% was covered in cycle 3 with left-looking imagery intended for stereo-radargrammetry use with data from cycle 1.

The Magellan Radar Sensor

Many geologists are familiar with the techniques of photogeologic mapping and have a working knowledge of standard aerial photography, satellite images, and stereoscopy (or stereopsis). SAR images acquired at 12.6-cm wavelength, however, are different from photographs and images acquired in the visible wavelengths. Radar returns vary according to several parameters such as wavelength, polarization, incidence angle, large- and small-scale surface roughness, and electrical and other physical properties of the surface. Thus geologic mappers will need to be familiar with the basic design and functioning of the Magellan radar system and how the radar data were acquired and processed so that they can make correct analyses of the data.

The Magellan spacecraft carries a single scientific instrument—a multi-mode radar sensor that operates in burst cycles, each consisting of sequential synthetic aperture radar (SAR), altimetric, and radiometric measurements (Saunders and others, 1990, fig. 2; Saunders and Pettengill, 1991; Ford and Pettengill, 1992; Michaels, 1992, table 1 and fig. 1). The SAR and altimeter are active sensors that allow measurement of the surface backscatter reflectivity in oblique and near-nadir (vertical incidence angle) viewing geometries, respectively (Pettengill and others, 1991). The radiometer measures the thermal emission of Venus at microwave frequencies by sampling the SAR receiver output when radar echoes are absent. The SAR and the radiometer operate through a narrow bandwidth, high-gain antenna (HGA), while the altimeter uses a separate, smaller horn antenna (ALTA) positioned to the side of the HGA. Magellan's SAR operates through the HGA at angles of incidence between about 17° and 45° from the local surface normal. Incidence angles are smallest toward the poles and largest at periapsis, near lat 10° N. (Pettengill and others, 1991; Saunders and others, 1992; Tyler and others, 1992).

During its nominal mapping mission, Magellan produced 7.3 orbits of image data per day. Each of those orbits imaged a strip about 20 km wide and 17,000 km long from the north pole to south of lat 70° S. Attributes of the three Magellan radar modes are discussed below.

Synthetic aperture radar (SAR). Synthetic aperture radar (fig. 2) is a method of using radar to improve the imaging resolution in the direction of motion for data gathered by airborne or spaceborne radar instruments. (This direction is called the "along-track" or azimuth direction.) The echo signal measured by the SAR receiver along Magellan's orbit is the coherent sum (accounting for both amplitude and phase) of many individual scattering events initiated by an incoming radar pulse (Tyler and others, 1992). When multiple echoes are combined, they effectively mimic (or synthesize) the performance of an antenna that has a much longer aperture along the spacecraft track. (The many echoes can be discerned on the basis of their Doppler shifts; see Tyler and others, 1992, fig. 3.) Each measurement of the power reflected back from a resolution cell is a single estimate of a random variable whose mean is the backscatter radar cross section. If N of these estimates or looks are averaged to obtain a mean, then the standard derivation of this measurement of the mean is equal to mean/$\sqrt{N}$. For Magellan, the number of looks (N) varies from 4 near the equator to 16 at the poles.

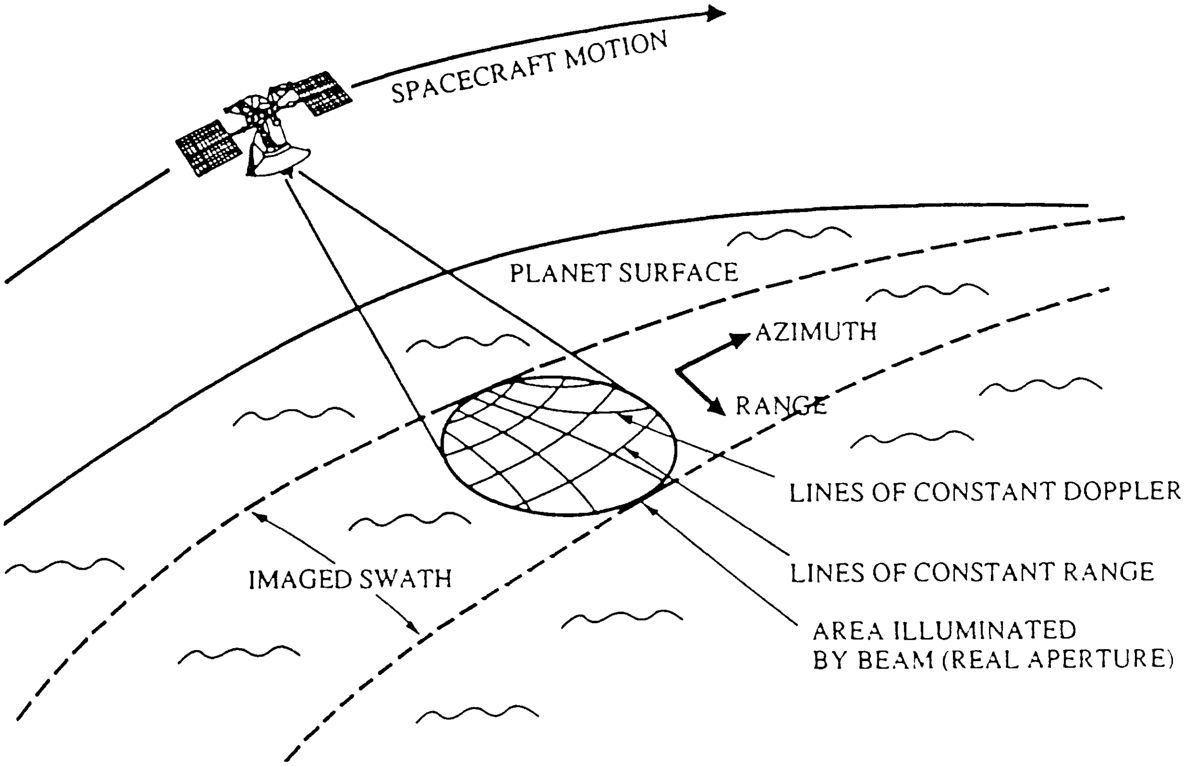

Figure 2. Method of data acquisition by the Magellan synthetic aperture radar (SAR) system; see text for discussion. (Reprinted from *Engineering & Science,* Spring 1991, v. LIV, no. 3, p. 16)

The Magellan SAR was designed to produce a 120-m along-track or azimuth resolution. The resolution in the other direction, called "cross-track" or "range," is governed by normal techniques of pulse encoding common to most radars and is a function of transmitted bandwidth and incidence angle. For Magellan, the range resolution varied from about 120 m near periapsis at lat 10° N. to about 280 m near the poles (Michaels, 1992, figs. 16, 17).

Several parameters interact to control SAR image quality. The most important are spatial resolution, the number of "looks," amplitude resolution, signal-to-noise ratio, and incidence angle. For the Magellan SAR, the angle between the incident radar energy and the surface normal (the incidence angle) was varied to maintain an acceptable ratio of signal-to-noise as the altitude of the spacecraft above the surface varied due to the elliptical orbit. Decreasing the angle of incidence increases the returned power because of Venus' relatively steep scattering law at 12.6-cm wavelength, and thus the decreased angle compensates for the increased signal loss as the distance to the surface increases (Pettengill and others, 1991). The key parameters of Magellan's radar imaging system, as well as those for previously acquired radar data, are given in Table 1 of Michaels (1992).

The 12.6–cm wavelength of the Magellan SAR, chosen for its ability to penetrate the dense Venusian clouds, causes the radar return echoes to be sensitive to the roughness of surface structural elements on scales of tens of centimeters to tens of meters. Magellan backscatter data were resampled at a pixel spacing of 75 m for the construction of images. Because of the variation of the backscatter cross section with incidence angle, the image pixel values are the log of the ratio of the measured mean backscatter cross section to the predicted value (based on a model of the average backscatter behavior of the surface of Venus as a function of incidence angle). The pixel (DN) values range between 1 and 251, and each increment of 1 DN corresponds to 0.2 dB. Relative accuracy of the radar cross section is less than ±1 dB cross track and ±2 dB along track. Performance checks during the mission verified that the radar sensor was operating according to sensitivity specifications.

Altimeter. The altimeter on Magellan measures the roundtrip time of the echo (and therefore, the distance) between the spacecraft and the surface (Pettengill and others, 1991). Many altimeter systems send out a single pulse and wait for an echo; however, because of the orbital altitude and the need to improve the signal strength, the Magellan radar altimeter was designed to transmit 17 pulses and then to "listen" for their echoes. The pulses are transmitted and received through the altimeter horn antenna part of the beam, which is always pointed down toward the subsatellite or nadir point. The strongest echo usually comes from the nadir direction, but in regions of high relief the echo can be contaminated with echoes from nearby areas. The altimeter "footprint" is very broad (10 x 12 km at periapsis to 20 x 29 km near the poles), and several techniques are used to determine the spacecraft–to–surface distance. These data are combined with information on the spacecraft position relative to the planet's center of mass to produce a topographic map, which shows the elevation relative to a mean planetary surface (Ford and Pettengill, 1992).

Radiometer. The Magellan radiometer experiment indirectly measured the 12.6-cm-wavelength radio emissivity of the Venusian surface. Thermal radiation at radio wavelengths, received from an object whose physical temperature is known, can be used to estimate the object's emissivity, a quantity that is largely controlled by the electrical properties of the radiating surface; the emissivity is also sensitive to surface roughness (Pettengill and others, 1992). Under complementary viewing geometries, the surface emissivity is equal to one minus the Fresnel reflectivity. For Magellan, this relationship is only approximated, because the thermal emission is measured with the high-gain SAR antenna, while the Fresnel reflectivity is estimated using the nadir-pointing altimeter horn. For materials that do not conduct electricity, the emissivity and Fresnel reflectivity are mainly determined by the dielectric constant of the surface material. The emissivity is also affected by the degree of surface roughness, whereas, as indicated earlier, obtaining the Fresnel reflectivity from the altimeter data depends on being able to estimate the fraction of the footprint of the altimeter antenna that is contributing to diffuse scatter—a process fraught with considerable uncertainty (Pettengill and others, 1992).

The 2° beamwidth of the Magellan high-gain antenna yields surface resolutions that range from 15 km by 23 km at periapsis to about 85 km at the north pole. Measurements of emissivity carry an absolute error of about 0.02 and can distinguish local variations as small as 0.005 that may be due to variations in small-scale surface roughness, density of surface materials, or composition (Pettengill and others, 1992).

Analysis of Magellan Radar Data

SAR backscatter images. To geologic mappers, radar images are similar to visual-wavelength photographs and images in that they reveal the morphology and texture of the surface. Morphology is evident because coarse-scale topography modulates echo strengths, which tend to decrease with increasing incidence angle. (See Ford and others, 1989, fig. 2, for a diagram that depicts terms used in describing radar imaging angles.)

Magellan radar echoes result from two scattering mechanisms: diffuse and quasi-specular. Diffuse scattering occurs when the surface is rough at wavelength scales and the incident radar energy is scattered into a broad range of angles. The opposite occurs when the surface is smooth over several wavelengths or more; the incident energy undergoes a quasi-specular, or mirrorlike, reflection that is directed back toward the radar when the surface is perpendicular to the line of sight from the radar (Hagfors, 1964; Tyler and others, 1971). Quasi-specular scattering dominates the echo from Venus at 12.6 cm for small angles of incidence; it decreases sharply with incidence angle and becomes weak relative to diffuse scattering at about 30° (Tyler and others, 1992, fig. 2).

Diffuse scattering contributes to the echo at all angles of incidence; the return power decreases roughly as the cosine of the incidence angle (i.e., at incidence angles $>30^{\circ}$, echo strength is a relatively weak function of incidence angle). Thus, in the radar images of Venus, areas with slopes tilted toward the radar are `brighter' (i.e., they backscatter more signal than the average surface) due to an increase in the diffuse and/or quasi-specular backscatter cross sections; slopes tilted away from the radar appear dark and resemble shadows. (However, true radar shadows may or may not be present, depending on the relative sizes of the surface slope and incidence angle.) These slope-induced modulations of the echo strengths in radar images produce shading similar to that of visual illumination. Thus, local topographic features such as domes and ridges can be identified with reasonable certainty.

Over broad areas, the variations in backscattered echo power are primarily due to variations in the diffuse backscatter cross section; the incidence angles at which the surface was observed during cycles 1 and 2 were greater than 25° except in the polar regions at latitudes above 60° (see figs. 8 and 9 of Michaels, 1992). The diffuse backscatter can vary due to differences in the physical properties of the surface, primarily the degree of wavelength-size roughness, or to differences in the electrical properties (and, hence, the intrinsic or Fresnel reflectivity) related to compositional differences. The Magellan images exhibit both of these phenomena. It seems clear that the extensive, very bright, high-backscatter areas corresponding to elevated terrains such as Ishtar Terra, Aphrodite Terra, and Beta Regio are related to compositional differences; this may also be true for the interior floors of a few craters. At lower elevations, the large-scale differences in backscattered power appear to be primarily due to differences in wavelength-scale surface roughness. This implies that the dark circular and parabolic haloes around craters and the dark lava flows have surfaces that are smooth at the scale of a few centimeters or less, while the very bright lava flows of Lavinia Planitia and many other areas have surfaces that are very rough at scales of a few centimeters or larger. Weathering, erosion, and surficial deposition (produced by impacts, volcanism, or wind) may alter the radar-backscatter signature of a surface over time (see Arvidson and others, 1992; Plaut and others, 1992).

Incidence angle also largely governs the geometric distortion of topography in SAR images. Because in the translation of radar-echo-time delay into distance on the surface we assume a 'flat' surface, slopes facing the radar beam appear foreshortened, whereas slopes facing away are lengthened. Thus, mountains, hills, and ridges appear to 'lean' toward the radar beam. This distortion increases with decreasing incidence angle (Ford and others, 1989, fig. 29). When slope angle exceeds incidence angle, the echo from the top of the slope arrives before the echo from the bottom, resulting in 'layover'; in this situation, the translation from echo-time delay to distance fails (see Magellan example in Ford and Pettengill, 1992, figs. 4 and 5). On the other hand, if a back slope is steeper than 90° minus the incidence angle, it cannot be viewed by the radar and results in an area of shadow. Thus, an observer should be particularly wary of geometric distortions at low incidence angles in areas of high local relief. Radar foreshortening, however, can be used advantageously to calculate the approximate height and slope of a topographic feature that is symmetric across track (Michaels, 1992, fig. 15).

Another geometric anomaly arises from the high sensitivity of the imaging radar to steep slope at moderate to low incidence angles. This sensitivity enhances the perception of linear topography on images. Because radar responses are strongly directional, the ability to discriminate linear features on images varies with the orientation of the features relative to the illumination vector. Landforms that appear prominent on images where they are transverse to the illumination direction may not be evident on images where they are parallel to the illumination (see Wise, 1969; Yamaguchi, 1985). Thus, minor structures otherwise detectable may not be seen where they trend eastward. There are also a small number of examples of differences in backscatter intensity over large areas between right- and left-looking radar images made at the same incidence angles. This implies a systematic azimuthal asymmetry in the surface structure similar to, say, sand dunes, but the cause of the asymmetry in the Magellan imagery is not known (Plaut and others, 1992).

Altimetry, rms slope, and reflectivity. Both the height resolution and the surface spatial resolution (footprint) are determined by the 0.59-µsec delay resolution of the SAR transmitter. As spacecraft altitude increases, the nominal height resolution does not change, but the footprint size changes from 10 x 12 km at periapsis to approximately 20 x 30 km at high latitudes (Pettengill et al., 1991; Michaels, 1992). Depending on the surface terrain, relative height accuracies can approach 5 m, although orbital uncertainties limit the absolute accuracy to greater than 50 m. In very rough terrain, the accuracy is limited by the inherent 0.59-µsec time resolution to about 90 m (Pettengill and others, 1991). Again, in very rough terrain, the precise reflection point within the spatial footprint is uncertain, which can be a significant source of height error.

The arrival time, amplitude, and shape of the time-dispersed echo from each transmitted pulse from the altimeter horn is dependent on the terrain height, surface reflectivity, and surface roughness at both wavelength and larger scales for the area contained within the altimeter horn antenna footprint. The arrival time of the leading edge of the echo provides information about the surface height, the total integrated power in the echo provides an estimate of the backscatter cross section at normal incidence, and the shape of the echo (i.e., the amplitude as a function of time) is a measure of the rms surface slope within the antenna footprint. The backscatter cross section as a function of incidence angle (the scattering law) out to about 10° can be derived from the shape and fitted to any of a number of theoretical scattering functions. The one chosen for Magellan analysis was derived by Hagfors (1964) and has been found to provide a good fit to the behavior of the quasi-specular scattering out to incidence angles of approximately 25°, larger than the 10° or so encompassed by the altimeter data. Hagfors' law has a single free parameter, the 'C' parameter, where $C^{-1/2}$ is a measure of the rms surface slope at scales of about 1 m and larger. Surfaces with high 'C' values (a C of 1000 corresponds to an rms slope of about 2°) are relatively smooth and have a scattering law that is sharply peaked near zero incidence angle. Rough surfaces (a C of 100 corresponds to an rms slope of about 6°) have scattering laws that tail off relatively slowly with incidence angle. The validity of the Hagfors' scattering function, as well as the role of subsurface and multiple scattering (not included in the Hagfors formulation), are subjects of continuing study (Pettengill and others, 1991). A second method of analysis involved direct inversion of the delay and frequency spectra from nadir to 10° incidence to derive a model-independent measure of the radar-scattering function, as described by Tyler and others (1992). These scattering functions yield information on the average small-scale surface structure (tens of centimeters to tens of meters) for surface elements hundreds of square kilometers in size.

With a well-calibrated radar system like Magellan's, the measured scattering law provides a good estimate of the backscatter cross section as a function of incidence angle out to 10°. By fitting Hagfors' scattering law to the data, or by measuring the total power under the measured scattering function, it is possible to estimate the Fresnel reflectivity of the surface. However, there is an assumption that all the signal reflected from the surface is scattered within a 10° cone, which implies no high-angle or diffuse scatter from the surface. This is normally probably not the case, and estimating the Fresnel reflectivity becomes much more difficult. By using the SAR backscatter cross section and assuming that the quasi-specular component of the reflection obeys Hagfors' law, it is possible to estimate the fraction of the surface within the altimeter antenna footprint, which scatters diffusely, and to use this fraction to improve the estimate of the Fresnel reflectivity (Tyler et al., 1991). The final values should still be treated with some caution.

In the above discussion we have implicitly assumed that the surface of the altimeter antenna footprint is statistically homogeneous. This is clearly often not the case. If the footprint is over the edge of a crater, then a double-humped response may be received corresponding to echoes from the rim followed by echoes from the crater floor. The measured height, rms slope, and reflectivity are then very dependent on the relative amplitudes of the two echoes and the algorithms used to derive the parameters. In areas with steep average slopes, the area contributing the maximum return will be offset from the nadir, leading to a possible height error. Consequently, in areas of complex terrain, the mapper should be very careful in the interpretation of all the parameters derived from the altimeter data. Individual altimeter measurements, which are spaced as close as 2 km, can be examined independently for detailed topographic analysis.

The nominal mission provided 3 x 10^6 altimetry measurements from lat 85° N. to lat 80° S.; vertical resolution is about 80 m. Cycle 2 measurements were made halfway between those of cycle 1 so that a more complete dataset could be achieved. From this dataset, a global topographic base has been produced that has a 5-km pixel size (Ford and Pettengill, 1992, plate 1). Overall, the Magellan altimetry data show that Venus has a unimodal distribution of topography; about 80 percent of the surface is within 1 km of the mean planetary radius (6051.84 km). Also, steep slopes (>30°) are measured along mountain fronts (for example, those of Maxwell and Danu Montes) and in canyons (such as Diana and Dali Chasmata) in the equatorial highlands (Ford and Pettengill, 1992).

Stereoscopy. Stereoscopy can be employed for paired images having the same illumination direction. Incidence-angle differences of 10° to 20° produce optimal parallax (Ford and Pettengill, 1992). Subjective height perception from Magellan stereopairs produces a vertical exaggeration of 6 times—about twice that of typical stereopairs of aerial photographs (Leberl and others, 1992). The geometric accuracy of Magellan stereopairs is theoretically about ±0.6 pixels, or ±30 m vertically; elevation differences within a stereopair are expected to be accurate within ±100 m (Leberl and others, 1992). Computer-generated stereo measurements under development may attain an accuracy of about ±2 pixels.

Some actual radar stereo test images with same-side (with different look angles) and opposite-side geometries were acquired of a few selected targets during Magellan cycle 2 with considerable success. Additional stereoimage data were acquired during cycle 3. The topography produced from actual radar stereoimages retains the spatial resolution of the original data, a great improvement over the lower resolution synthetic stereoimages. Thus, interpretation of relatively small landforms and structures is enhanced. For example, in measuring the average relief of lava flows, Moore and others (1992, table 2) were able to estimate thicknesses in the range of several tens of meters; in a test case, their measurement error was ±1.8 pixels, which corresponds to ±34 m.

Emissivity. Global mean emissivity is about 0.85, which corresponds to a dielectric permittivity, or dielectric constant, of 4.0 to 4.5. These values are consistent with dry basaltic minerals. However, at high elevations (>6054 km planetary radius), some surfaces are highly reflective (with corresponding emissivities as low as 0.3); this relation may indicate a weathering process that results in a surface material having a high dieletric permittivity (of about 80) or a material with average permittivity but many voids that cause multiple scattering within it (Arvidson and others, 1992; Pettengill and others, 1992). A few large impact-crater floors also have low emissivities that may result from compositional differences (Weitz and others, 1992).

Magellan Data Products

SAR image data records. Magellan radar data are processed and mosaicked into spatial image products to facilitate scientific analysis. The standard data products include image mosaics and ancillary data. Other special products include altimetric, rms slope, reflectivity, and radiometric datasets in image form for science analysis. A particularly useful portrayal is the superposition of color-coded datasets on the SAR backscatter data records (for example, Arvidson and others, 1991; Tyler and others, 1991; Kirk and others, 1992; Pettengill and others, 1992; Sandwell and Schubert, 1992). SAR mosaics are further processed to generate the scaled quadrangles that are used for map bases in the VMAP program. Both synthetic and real parallax stereopairs of Magellan image mosaics are being produced as well; the synthetic ones have parallax offsets generated by computer on the basis of Magellan altimetry data.

One Full-Resolution Basic Image Data Record (F-BIDR) was produced for each Magellan orbit; 1,790 orbits complete one mapping cycle (360° of longitude). (For the primary mission, solar conjunction prevented the return of SAR data for 110 orbits.) An additional 10 percent was lost during the nominal mission because of solar heating of electronic components (the spacecraft's solar reflectors had lost much of their efficiency), failure of one of the spacecraft's two tape recorders, and problems affecting spacecraft attitude. One F-BIDR contains nearly 60 Mbytes of 8-bit image data and less than 10 Mbytes of ancillary data. The F-BIDR format is 75 m/pixel resampled from the original ≥120-m cross-track and along-track resolutions and transformed into Sinusoidal Equal-Arèa projection; within 10° of the poles, the data are in oblique Sinusoidal projection (the F-PIDR format). Each F-BIDR forms a strip about 300 pixels wide by about 220,000 pixels long. In turn, about 30 F-BIDRs (or more at higher latitudes) are used to generate a mosaic, which has 7,168 lines by 8,192 samples. The mosaics are called Full-Resolution Mosaicked Image Data Records (F-MIDRs). Each F-MIDR is identified by center latitude and longitude and covers 5° of latitude and >5° of longitude (depending on latitude; see Michaels, 1992, figure 4). A "venetian blind" effect is commonly evident in mosaicked F-BIDRs because of border mismatches in backscatter intensity caused by minor errors in spacecraft pointing and navigation, in the topography model, and in processing.

To provide image-mosaic coverage for larger areas, the data are compressed in successive operations in which nine pixels are averaged and replaced by one pixel and then reprojected. The Once-Compressed Mosaicked Image Data Record (C1–MIDR) consequently has a resolution of 225 m/pixel and covers 15° of latitude and >15° of longitude (see Michaels, 1992, figure 5). In turn, successive compressions result in the 675 m/pixel C2–MIDRs (45° of latitude by >45° of longitude; Michaels, 1992, figure 6) and the 2,025 m/pixel C3–MIDRs (80° of latitude by >120° of longitude). Polar data records (F–PIDRs) and projections (P–MIDRs) portray areas at >80° latitude.

The various MIDR products are being distributed as photographic prints and digital files on CD–ROM disks. The CD–ROMs released by the Magellan Project are available to the planetary geoscience community through the National Space Science Data Center in Greenbelt, Maryland.

Synthetic stereopairs and merged databases. Synthetic parallax stereoimages of most of Venus based on C1–MIDR image mosaics have been produced by the U.S. Geological Survey for the Magellan Project as preliminary tools in assessing the global geology of Venus. These synthetic stereoimages are produced by (1) geometrically registering to a single Magellan image mosaic the best available altimetry dataset (10 X 12 km to 20 X 29 km resolution, depending on spacecraft altitude), and (2) introducing parallax into the MIDR, as controlled by the registered geometry (that is, shifting pixels left or right by a distance proportional to the altitude relative to the average altitude in the MIDR, so that the overall average shift is zero pixels). Vertical exaggerations have been produced at 10X and 50X. These stereoimages will be important for interpretations of the broad topography, which will be valuable in analyzing the larger landforms associated with volcanism and tectonism.

In addition, perspective views can be generated from the merged topography and SAR image mosaics. Other radar databases (emissivity, reflectivity, rms slope, etc.) can be colorscaled and combined with black-and-white SAR mosaics for normal or perspective views or for synthetic stereo analysis.

Map projections. To assist in various cartographic endeavors, formal map series are being produced at various standard scales and projections. Such maps will be used as base materials for geologic mapping. The VMAP program is sponsoring geologic mapping of the 1:5,000,000–scale series that consists of 62 quadrangles (fig. 1). The series includes Mercator (<25° latitude), Lambert Conformal Conic (25° to 75°), and Polar Stereographic (>75°) projections. All are conformal projections, which retain the approximate shape of small landforms. However, all are distorted across larger regions. The Mercator base, visualized by a cylinder perpendicular to the equator, is conveniently rectangular, but scale changes rapidly with latitude (Batson, 1990, fig. 3.1). For Venus, the cylinder intersects at ±15.9° latitude, where the true 1:5,000,000 scale occurs. The Lambert Conformal Conic projection is represented by a cone tangential to the globe whose apex intersects the spin axis of the planet (Batson, 1990, fig. 3.3). The latitudes of cone–globe intersection are called standard parallels. Scale changes with latitude. For Venus, two rows of these projections occur in each hemisphere with standard parallels at 34° and 73°, where true 1:5,000,000 scale occurs. Polar Stereographic projections represent planes tangent to the axial pole (where true scale occurs). The scales of the projections are the same where they join (at lats ±25° and ±75°).

Other map series that are being produced for Venus contain 340 sheets (Sinusoidal) at 1:1,500,000 scale, 8 sheets (6 Mercator and 2 Polar) at 1:10,000,000 scale, 3 sheets (2 Mercator and 1 Polar) at 1:25,000,000 scale, and 1 sheet at 1:50,000,000 scale. For more information, refer to Batson (1990).

Non-Magellan Radar and Other Data

Since the early 1960s, Venus has become one of the planets most visited by spacecraft. Fifteen Soviet and six U.S. missions have probed its sulfurous clouds to measure atmospheric structure and composition. Other investigations disclosed a lack of water vapor and the absence of a magnetic field. Seven of the Soviet craft were landers that conducted chemical analyses of rocks, which indicated that some have compositions similar to basalt and thus may be of volcanic origin. One of the landers, Venera 9, gave us our first glimpse of the surface when, in 1975, it relayed a panoramic view. These early explorations were enhanced by observations in the field of radio astronomy that indicated that Venus is a perpetual furnace; surface temperatures reach 482 °C (~900 °F), and the atmospheric pressure is 90 times that of Earth's (Young, 1990).

The 1978 U.S. Pioneer Venus Orbiter (PVO) was the first spacecraft to carry a radar (SAR-type) sensor to Venus, and the altimetry of 92 percent of the surface was mapped at a resolution of 50 to 140 km. For the first time, planetary scientists had a global map of Venus. Continent-size highlands, hilly plains, large mountains looking like volcanoes, and flat lowlands were revealed (Masursky and others, 1980). Much of the initial scientific results from the Pioneer Venus mission were published in a special issue of the Journal of Geophysical Research dedicated to that mission (December 1980, v. 85, no. A13, p. 7575-8337).

Five years after Pioneer Venus went into orbit, the Soviet Venera 15 and 16 spacecraft used radar to map about 25 percent of Venus (lat 25-90° N.) at a resolution of 1.2 to 2.4 km. These images revealed evidence of abundant volcanism, impact craters, and complex tectonic deformation, including coronae—large, oval features of apparent volcanotectonic origin previously unrecognized on other bodies in the Solar System (Kotelnikov, 1989). The geoscience investigations of Venera 15 and 16 are described in many publications (see Recommended Reading).

Earth-based radar observations of some regions of Venus have been made primarily from the Arecibo Radio Observatory and the Goldstone receiving station since the mid-1960s (see, for example, Jurgens and others, 1980, 1988a, b; Burns and Campbell, 1985; Campbell and others, 1989, 1990; Campbell and Campbell, 1992; Plaut and Arvidson, 1992). The Goldstone radar coverage is restricted to lat 23° S. to 23° N. and long 260° to 32° E. (Plaut and Arvidson, 1992), while that from the Arecibo Observatory is limited to most of the area between lat ±67° and long 265° to 35° E., about 23 percent of the surface (Campbell and others, 1990). In all, about 40 percent of Venus has been mapped from these radar stations (Campbell and others, 1990).

GEOLOGIC MAPPING OF VENUS

The basic objective of the coordination efforts of the Venus Geologic Mapping Program is to ensure that the geologic maps have reasonable consistency (such as in usage of map–unit names and map symbols) and agreement, which will provide a useful basis for geologic interpretation. Mappers should be guided not only by fundamental geologic principles, but also by many precedents and approaches (some more applicable to Venus than others) that have been established through previous planetary mapping programs and various early mapping studies of Venus. (See Recommended Reading; in particular, the book chapter by Wilhelms (1990) should be regarded as *essential* reading.) In addition, mappers will face the new challenges of the distinct geologic character of Venus, broadly and in detail, and of the nature of the radar datasets. Mappers should follow guidelines of the USGS; even though adherence to basic mapping principles is a must, mappers have considerable latitude in their application and are encouraged to investigate new approaches that may result in a more instructive and useful geologic map. For example, structurally complex terrains generally cannot be mapped as conventional rock (material) units; inclusion of terrain units may necessitate altering their depiction on correlation charts and cross sections. Also, additional small-scale maps depicting major tectonic structures or surficial features may be necessary to depict the geology of complex regions clearly and comprehensively.

Rationale and Methods

Defining map units. Map units will be defined on the basis of various morphologic, textural, and structural characteristics observable in Magellan images. *Geologic (or rock or stratigraphic) units* are made up of bodies of rock that are thought to have formed by a particular process or set of related processes over a discrete time span. Even though the interpretation of a map unit or its relative age may not be clear, the unit must have distinctive characteristics. Some surface rocks, however, are so modified by processes postdating their emplacement that their original key characteristics no longer are decipherable. In many of these situations, it is impossible to define geologic units with confidence. Rather than leaving the map blank, it is appropriate to map *geomorphologic units* that are based on the same types of characteristics, even though the characteristics developed much later than the emplacement of the modified rocks (see Milton, 1975). Where particular morphologic structures or other associated features are rare, the mapper should choose simply to discuss them in the unit description and perhaps map them as symbols rather than delineate a new unit based on them.

Some mappers may find that a different approach to defining map units is more suitable for their Venusian quadrangle. In particular, *tectonic units* should be considered. Until now, planetary maps have generally excluded tectonic mapping as has been practiced for the Earth. Tectonic mapping has been varied and highly subjective because of changes in paradigms used to interpret and understand terrestrial tectonics. Actually, mapping styles once used for the terrestrial continents—styles that predated our understanding of plate tectonics—appear most applicable to Venus, because they distinguished rocks and terrains associated with foldbelts and cratons (see King, 1969a, b; King and Edmonston, 1972). King promoted a relatively conservative style (although much of the terminology of his day is losing favor among geologists). He stated (1969b, p. 87) that a tectonic map "portrays the architecture of the upper part of the earth's crust, or the features produced by deformation and other earth forces, and represents them by means of symbols, patterns, and colors." Recently, because plate tectonics has gained wide acceptance because it explains much of terrestrial tectonics, the mapping of *tectonostratigraphic terranes or elements* has become popular (for example, see volume edited by Howell, 1985). Such units are understood to be fault bounded and defined according to stratigraphy, tectonic disruption, or metamorphic overprint. Small-scale mapping of these units caters to accretionary plate tectonics (see Howell, 1985, map insert; Dickinson and others, 1986).

Units should be mappable on Magellan SAR backscatter image mosaics, which form the primary dataset that permits identification of morphology and structure. Unit descriptions should be augmented by radar characteristics such as radar "brightness," backscatter coefficients, emissivities, reflectivities, rms slopes, and topography from altimetry (for example, see Arvidson and others, 1992, fig. 7 and table 1; Moore and others, 1992, table 3). However, mappers should avoid defining units solely by such characteristics, which may be related to weathering or deposition of thin eolian or impact material and have little or nothing to do with the emplacement or structural modification of the affected map unit (Arvidson and others, 1992; Greeley and others, 1992). Also, the nonbackscatter radar data seldom clearly define mappable areas because of their common variation with respect to surficial rock properties and relatively low resolution. Where stereopairs are available, stereoscopy adds the important dimension of local relief for characterization of geologic units at a scale that is not possible with Magellan altimetry or synthetic stereopairs; stereoscopy enhances geologic mapping and interpretation to a degree that cannot be overestimated.

Units may have distinct contacts, perhaps expressed topographically or by cross–cutting and overlap relations. Where contacts are indistinct, mappers may make them long-dashed or queried (which signifies, respectively, gradation or uncertainty). Alternatively, mappers may redefine the observational basis that distinguishes the units. As a last resort, units can be lumped.

Correlating map units. Contacts between map units are critical in defining emplacement relations and relative ages and should be clearly presented on the map. Contact geometry may suggest overlap, embayment, crosscutting, or abutment relations that may be used to infer relative age. Structural relations may also be useful in determining relative age.

On Venus, relatively late resurfacing and a thick atmosphere have resulted in crater densities that are too low for detailed stratigraphic work; thus far, only 921 impact craters have been identified on about 98 percent of the surface. Over broad areas of Venus, crater densities are spatially random (Schaber and others, 1992), although lower than average densities of some areas are interpreted to be related to extensive volcanic resurfacing and tectonism (Phillips and others, 1992).

The global chronology of Venus will be determined through the collective efforts of the geologic mappers, who will establish the local geologic history within their individual map areas. Time markers may include widespread geologic and geomorphologic units, structures, and surficial signatures related to impact events or weathering (Izenberg, 1992; Tanaka and Schaber, 1992).

Mapping approach. (This section is largely distilled from Wilhelms, 1990, section 7.4.) Initial familiarity with the map area is achieved by reconnaissance mapping. This first step reveals the overall geology and identifies major map units, their stratigraphy, and structures. To explain the geologic evolution of the area, working hypotheses are formulated that can be tested and revised as more detailed mapping proceeds. The reconnaissance also assists in identifying the most significant and challenging problems in the area, whose resolution will be the major objective of the mapping.

Detailed mapping is best started where units and contacts are most clearly mappable. Commonly the location is determined by the availability of the highest resolution data. Thus, where FMIDRs are available, they can be individually used for mapping in greater detail than can be shown on the quadrangle, which will provide the mapper with a more complete understanding of the local geology. Another approach is to map younger units first—these units are generally better exposed, and their relative age relations are easily portrayed. A working set of map units and symbols is generated and then modified as mapping progresses. Where key features (such as small volcanoes) are too small to map as units, they may be portrayed as map symbols. Ultimately, the level of detail shown on the maps will be dictated by scale and perhaps ancillary data such as stereopairs and FMIDRs.

Other datasets can be incorporated in the mapping as appropriate, including SAR backscatter cross section, topography, emissivity, reflectivity, and rms slope. However, radar characteristics in most cases constitute a poor basis for unit definition because of their dependence on surficial properties. Some units may even be difficult to map consistently on the basis of SAR backscatter, because backscatter intensity varies according to incidence angle and, in some cases, look direction. If mapping of surficial characteristics is desired, it should be regarded as secondary in importance to mapping of geologic materials and structure and shown in a separate map figure.

As in traditional field mapping, note-taking is vital in documenting the mapping procedures and approach used and in highlighting key geologic observations and relations. Such observations include morphologic characteristics, overlap and cross-cutting relations, and evidence for style and sense of structural deformations. A notebook dedicated solely to the map is very valuable; in it, extended notes can be located by annotations, perhaps on a map overlay. Such documentation contributes to the production of a thorough, well-balanced, consistent, and insightful interpretation of the geology of the map area.

After an initial set of associations and age relations among map units has been derived, a correlation chart consisting of boxes for each map unit can be developed. Map units generally lend themselves to grouping according to terrain type or geologic or geographic associations. Hierarchic names include many possibilities that reflect what the units have in common, such as terrain type (for example, plains, plateaus, mountain belts, shields, and canyons), perhaps subdivided according to local individual geographic features. When the association is based on a geographic feature, the name of the feature coupled with descriptive terms such as "assemblage" or "sequence" will form the hierarchic name. Relative ages of the map units are represented on the correlation chart by vertical position. Thus units that are clearly younger should be shown above older units; those that overlap in age will have boxes that overlap vertically. Because some units developed over a considerable timespan, their boxes may be much longer than those of other units. For a poorly defined age limit, a sawtooth box edge should be used. Boxes for closely related units share a box edge that is horizontal or vertical as appropriate; where their ages overlap, they may share a diagonal box edge. (See examples of planetary geologic maps cited below.) Where geologic and structural relations are complex, informal cross sections can be attempted as tests of possible scenarios of development. Preliminary correlation charts and cross sections are excellent tools to identify areas and relations that require more careful examination.

Coloring the preliminary map as parts are completed is the best way to identify incomplete contacts, incorrect symbols, and inconsistencies in mapping style. Other special maps, perhaps of selected areas at larger or smaller scales, may be used to show tectonic structures or surficial materials and features. Such maps not only highlight specific aspects of the geology, but they also may reduce the clutter on the primary geologic map. In a few instances, particularly in areas of high relief, a schematic cross section can be added to interpret structure; these sections generally have a vertical exaggeration, which is stated.

When the mapping is complete, the description of map units (DOMU) and text can be written. The DOMU describes the map units shown on the correlation chart according to groupings in the hierarchy, from youngest to oldest (in reverse chronologic order—opposite the oldest-to-youngest order used in the text's discussion of stratigraphy). Descriptions and interpretations of units are always clearly separated. The description should include the unit's physical characteristics, occurrence, and relations with other units. The interpretation may include the inferred rock type and mode of origin of the unit; multiple interpretations may be included. Map symbols are explained after the DOMU. The map text should include an introduction that describes the basic geologic setting and physiography of the map area, relevant previous work, objectives of the mapping, and constraints of image resolution that may have affected it. The body of the text should reconstruct in detail the geologic history (from oldest unit to youngest) on the basis of map relations and interpretations. However, the discussion should not include directed, refined geologic analyses typical of those found in research articles.

Type of Mapped Units and Features

Prior to Magellan, small-scale (1:15,000,000) geomorphologic mapping of the northern quarter of Venus was based on kilometer-resolution radar mosaics imaged by the Venera 15 and 16 SARs (Sukhanov and others, 1989; Schaber, 1990; Schaber and Kozak, 1990). At that resolution, many important geologic (especially stratigraphic) relations were not discernible. However, the higher resolution Magellan data permit more detailed and "classic" stratigraphic and structural mapping and interpretation, as can be seen from examples in recent journal articles. These various examples are useful in visualizing how map units can be defined and how contacts and various structures can be mapped. (Keep in mind that the published examples use various names and conventions that may or may not be appropriate for VMAP). This section is divided into discussions of the major types of terrains and structures to be mapped on Venus.

Plains materials. Plains units generally are characterized by relatively smooth-appearing (at image resolution) surfaces at low to intermediate elevations. Relative ages are determined by embayment and cross-cutting relations. Units can be subdivided according to morphology (for example, smooth (at pixel scale), ridged, hummocky, fractured, complex); geographic and terrain associations; relative stratigraphic position (such as lower, middle, and upper); and, *locally*, radar brightness (for example, bright, dark, mottled; see Solomon and others, 1992, fig. 32);

Lava flows and volcanoes. In some areas, individual or multiple lava flows can be subdivided according to radar brightness, superposition, morphology, and surface texture (for example, Arvidson and others, 1992, fig. 6; Head and others, 1992, fig. 9a, d; Moore and others, 1992, fig. 4; Senske and others, 1992, plate 1). Large volcanoes may have distinctive and mappable summit or central caldera areas and associated structures (Head and others, 1992, figs. 3a, b, 4a–c, 5b; Senske and others, 1992, fig. 6). Small volcanic shields or domes may be outlined individually (Head and others, 1992, figs. 2b–d) or shown by point symbols. In some areas, flow directions can be indicated.

Structural terrains and features. The greatest challenge faced for many of the VMAP quadrangles is the mapping of structural terrains and features. A common mistake is to draw in as many structures as possible; this approach results in clutter and is not helpful to the reader. (Remember that the quadrangle base will portray much of the character of highly deformed map units.) Instead, map highly deformed terrains as units and trace only particularly significant or representative structures on the geologic map (compare King and Edmonston, 1972; King, 1990a). Structural terrains include ridge and fracture belts, tesserae (or complex ridged terrains), and other highly deformed areas. These terrains may be delineated on the basis of elevation, relief, dominant structural type(s), structural patterns, size of individual structures, and structure density (Solomon and others, 1991, figs. 7D and 8B; Bindschadler and others, 1992a, figs. 3–7; Fienen and others, 1992). Care will be needed in areas where structural characteristics change gradually; if units are not sufficiently distinct to map separately, it may be better to lump units and show gradational trends through the mapping of representative individual features.

Significant individual features can be mapped by symbols (see Appendix B). Many mappable Venusian features are tectonic structures; however, topographic features (ridges, troughs, depressions, and scarps) and erosional features (channels) also are common. Mapping of faults or folds requires some supporting evidence for the deformation (such as offset surfaces). If such evidence is absent, a dashed or queried symbol, a less interpretative structural feature (for example, fracture instead of fault or graben), or a topographic feature (ridge instead of fold) can be mapped instead. Regional structures may be distinguished from local structures on the map by a heavier line weight.

Many geologic mappers will find it advantageous to represent both detailed structure and large tectonic features on a separate base at a similar or smaller scale. For example, coronae and coronalike features differ greatly in structural detail (Stofan and others, 1992, figs. 2–5, 13). Even so, detailed structural mapping may be tedious (Head and others, 1991, fig. 7D; Squyres and others, 1992a, fig. 4c). Instead, representative features may be mapped and perhaps summarized by rose diagrams where appropriate (Head and others, 1992, figs. 5–8; Senske and others, 1992, figs. 9–12, 16, 17, 20; Squyres and others, 1992a, fig. 8d; 1992b, figs. 5 and 7). Simplified, smaller scale tectonic maps may also be drawn (see Senske and others, 1992, figs. 4, 19, 21). (All graphs and line work will be redrawn by the USGS Office of Scientific Publications, but mappers should follow guidelines in Hansen, 1991.)

Impact craters. A special type of structure shown on most planetary maps is the impact crater. On other bodies, generally only larger craters are mapped, consistent with map scale. But, because only about 900 craters are recognized on Venus, they are all significant and should all be mapped. However, craters smaller than about 20 km in diameter may have to be indicated by a map symbol. In addition to the crater rim crest, the outer boundary and facies of impact ejecta, floor material, secondary craters, ring structures, central peaks, and outflows can be mapped in many cases (Schaber and others, 1992, figs. 23, 25–27). Also, mappers may choose to subdivide craters into various morphologic classes (for example, Schaber and others, 1992, fig. 4). Extensive surficial features associated with craters (such as dark splotches) should not be mapped as geologic units, but they may be shown by stipple patterns or in a separate, reduced-scale figure.

Mapping Conventions

Unit names, letter symbols, and colors. (See also Wilhelms, 1990; Hansen, 1991, p. 43–52; Reynolds and others, in press.) The general practice in planetary mapping is to use descriptive informal names (such as crater material, ridged plains material, or fractured highlands material). Informal names should include a term that shows that the unit is either a material (geologic) or surface (geomorphologic) unit. Formal names are occasionally applied to stratigraphically distinctive or complex rock units in planetary geology (for example, "Medusae Fossae Formation" on Mars); a formal name requires a formal definition following as closely as possible the established guidelines of The North American Commission on Stratigraphic Nomenclature (1983) (see Hansen, 1991, p. 44–49). We discourage the use of formal names in early stages of mapping a planet, however, because experience shows that many unit definitions and portrayals change substantially through the course of several years of research. We also discourage use of jargon (for example, "tick"), because of the resulting confusion to general readers.

As in terrestrial mapping, the unit-letter symbol is an abbreviation of the unit name. Because a formal stratigraphic system has not yet been established for Venus, no capital letter representing a time–stratigraphic system will be included. The symbol should have as few characters as possible. Avoid ambiguous usage (for example, use *p* for plains and *pl* for plateau). The letters should be arranged such that the basic formational name is followed by modifiers for members and submembers (for example, "lower ridged plains material of the Artemis assemblage" would be "unit aprl"). Some mappers identify a sequence of unit members by subscripts, the stratigraphically lowest unit being designated 1. (Thus member 1 of the example given above would be "unit $aprl_1$.") In the map text, a unit's name is always used, with or without its letter symbol; the symbol never stands alone. A symbol may be queried on the map (for example, "aprl?") if the unit assignment is in doubt; the reason for the doubt should be given in the DOMU.

The Venus Geologic Map Series will follow a consistent color scheme to the extent possible. Colors on the published maps are limited by the USGS color palette and will be selected by the map coordinator. However, authors should adopt the following general guidelines on their author-colored ("mill") copies—*browns* for older or heavily deformed terrains and units, *purples* for less heavily deformed terrains, *greens and blues* for plains units, *reds and oranges* for volcanic materials, *yellows* for craters, and *grays* for other materials. In addition, stippled overlays can show surficial units, broad tectonic zones, etc., that are superposed on the other map units. Some variation from this scheme is occasionally warranted where many subdivisions of units are made and a wide selection of color shades is not available. In general, maps are more visually pleasing and easier to read if the areally large map units are represented by light shades (pastels) and the small, patchy units are darker or more intense. Also, the colors of adjacent units should display sufficient visual contrast so that they do not become confused. Areas of missing data will be left uncolored.

Line and point symbols. A host of line and point symbols is available to the mapper; where possible, symbols should be those standardized by the USGS for terrestrial maps (Reynolds and others, in press) or those used on published USGS planetary maps (such as those used for crater rims). Many of the symbols used on planetary geologic maps are shown in Appendix B. (If a new symbol is needed, the VMAP Coordinator should be consulted.) Symbols need to be used judiciously to reduce map clutter. Thus, mapping of most secondary morphologic features such as fractures, wind streaks, yardangs, or channels should be avoided or done sparingly; for example, one large arrow (rather than several small ones) can often be used to show flow direction. In many places topography will be visible on the SAR backscatter base of the published geologic map. If the mapper wants to highlight specific features, they may be shown on a supplementary map at reduced scale.

Although structural symbols are desirable and informative, their application in some cases may be highly conjectural and uncertain. Thus fault symbols should be avoided except where offset is evident or probable. Normal faults, grabens, and some strike–slip faults may be acceptable. However, suspected thrust–fault scarps and folds should generally be mapped as queried, dashed, or as topographic symbols (scarps and ridges); their structural interpretation can be discussed in the text or shown in cross sections.

Geographic names. The mapper will be provided with an index map showing all named features in the map area. Only geographic names officially approved or provisionally accepted by the International Astronomical Union (IAU) can be shown on the map or mentioned in the text; a name's provisional status must be indicated, usually by an asterisk after the name on the map. Reference to unnamed features should be made by latitude and longitude (all features mentioned in text or DOMU, if not shown on map or in figures, must be located by map coordinates). Note that many craters, coronae, and other geographic features do not have names (see Schaber and others, 1992, table A1; Stofan and others, 1992, table 1). If you feel that a feature needs a name, please consult with the USGS representative to the IAU; guidelines for naming features are given in Appendix C.

MAP COMPILATION, REVIEW, AND PUBLICATION

Careful, thorough map-compilation procedures help avoid inaccuracies; inconsistencies between the map, text, and DOMU; and an unbalanced portrayal of the geology. The use of general procedures and style guidelines established by the USGS for the submission, review, and editing of planetary maps will materially expedite review and publication of maps. In addition, discussions with and informal reviews by authors of adjacent maps permit amicable and informal resolution of differences *before* a map is submitted. A USGS convention requires that map borders match those of neighboring maps submitted earlier, and texts should agree with neighboring texts, *unless* the author of the later submittal explicitly justifies the differences.

Compilation

VMAP mappers will compile their work on a mylar (stable-scale) base registered to a quadrangle base at 1:5,000,000 scale; corner points will be marked or holes registration punched. A subdued half–tone version (or "brownline") of the map base on mylar will be supplied for drafting map contacts and symbols. Other available image databases, including left- and right-look SAR mosaics, altimetry (including synthetic stereopairs), and emissivity data, will be supplied to the mapper. Geologic mappers must prepare not only the geologic map but also supplementary charts, figures, and text that include (1) a correlation chart, (2) a discussion of the geologic history of the map area, including specific results and interpretations of stratigraphy, structure, and other geologic features and relations (with a reference list and optional acknowledgments, figures, and tables), and (3) a description of map units and symbols. Cross sections and supplemental, special–purpose maps (generally at reduced scale) are optional. Supplemental information about the map base (including an index map, scale, and cartographic notes on base) are not the author's responsibility; they are added by USGS cartographers and drafters.

Mapping is compiled on the half-tone cronaflex quadrangle base. The emulsion is on the back side of the cronflex, so that erasures of drafted work on the front side do not affect the mosaic. Preliminary reconnaissance mapping on a paper print or mylar overlay prior to final compilation on the brownline base can be very helpful. The submittal copy on the cronaflex base should be drafted in ink. The line weight for major structures should be clearly heavier than that used for contacts, but minor structures can be shown in a light line weight. Prior to submittal, the *mapper* should color a paper ozalid or photocopy of the brownline to ensure proper and complete labeling of units. At the same time, all intersections of three map units should be checked; contacts should be drawn to reflect correct relative age (younger rock units should embay older ones; erosional geomorphologic units should crosscut the eroded units). Coloring the younger units first will readily expose any mistakes in the portrayal of overlap relations. *Every outcrop* is given a letter symbol; not only are these labels helpful to reviewers, but they prevent drafting errors. (Later on, the colorproof and published map will not bear so many labels because "color carries," but at compilation stage the extra precautions are necessary.) Also, the positions of all line and point symbols have to correspond precisely with the location of the feature on the base (the drafters will attempt to follow precisely the *author's* linework). Other illustrations involving map units (correlation chart, special maps, figures, and cross sections) should also be colored and checked for similar errors and inaccuracies; for example, cross sections have to match the map at the surface and mapped stratigraphic relations must agree with those shown in the correlation chart.

The author should also carefully check for consistency among the map, illustrations, and explanation and text. Many times unit occurrences are discovered to be incompletely described or unit names and symbols inconsistently rendered. Another common inconsistency is to make lengthy one-sided arguments regarding the interpretation of a few units or structures. A more complete listing of common problems in geologic maps is given by Wilhelms (1990, section 7.4.9).

USGS manuscript-preparation guidelines should be followed. Extensive changing of the format of your manuscript to adhere to guidelines after preparing it can be a frustrating experience. Instructions for the format of map texts and DOMUs are provided in Appendix D.

Pay particular attention to following telegraphic style for the explanation, in which both definite and indefinite articles and forms of the verb "to be" are omitted and the map unit is understood as the primary subject. The unit's characteristics should be described first, from primary to secondary ones, followed by geographic occurrence (if not obvious on the map) and relations and associations with other units. Finally, the interpretation is set off at the end. For example:

> Ridged plains material—Forms smooth plains marked by northeast-trending wrinkle ridges; fractures and flow lobes rare; generally radar dark. Overlaps highly fractured unit of Artemis Chasma; buried along south edge by lobate plains material. *Interpretation:* Low-viscosity lava flows erupted from local fissures; deformed by compressional stresses related to development of Artemis Chasma

Mappers will also benefit from familiarizing themselves with relevant guidelines in Hansen (1991): "Preparing Maps and Other Illustrations" (p. 184–211) and "Formatting Survey Manuscripts for Review and Editing" (p. 250–264). The first of these sections provides guidelines primarily for terrestrial maps, thus it is advisable to examine recent planetary maps for format and style unique to them. Some informative examples are the geologic maps of (1) the western equatorial region of Mars (Scott and Tanaka, 1986), which has an extensive and complex correlation chart; (2) Valles Marineris (Witbeck and others, 1991), which is laid out over two sheets and has cross sections; and (3) Olympus Mons (Morris and Tanaka, in press), which has a special map at enlarged scale on a topographic base, text in pamphlet form, cross sections, and extensive figures. In regard to formatting, pay particular attention to the sections on general guidelines, formatting tables, and references cited. (More detailed guidelines for preparing references and a list of examples are given on p. 234–241 of Hansen, 1991.) Careful authors will also study the section on grammar, style, and wording entitled "Suggestions as to Expression" (p. 124–183); this is a misnomer, however, because "suggestions" commonly translates to "orders"! Finally, for the perfectionist who would like to prepare near–camera-ready copy, the Map Coordinator can supply you with a guide to all the formatting instructions used on USGS I–Series maps.

Submittal, Review, and Editing

After your map and accompanying materials have been prepared according to the above guidelines, you must include in your submission the "Manuscript Review and Approval Sheet" (reproduced in Hansen, 1991, p. 38–39). The author completes the top half of the front of the sheet; the Map Coordinator completes the bottom half. This sheet, also known as the "route sheet," is used to track USGS products and must accompany them through all prepublication stages. An individual's *signature* on the route sheet signifies that the individual is finished with his/her particular processing step. If a person first *initials* the route sheet, he or she is indicating the need for a second review prior to further processing; the author cannot send the map on to the next person named on the route sheet until the previous individual's signature is obtained, unless the Map Coordinator decides otherwise. Although the Chief of the Branch of Astrogeology is required to sign the map at the beginning and end of processing, the Map Coordinator effectively acts as editor–in–charge.

Reviews include a preliminary format review by the Map Coordinator, who will ensure that the submitted materials are in reasonably good order. The Coordinator will then pick two technical reviewers (preferably two who are in the VMAP program). Each mapper will be expected to serve as a technical reviewer on two maps. (Suggestions for map reviewers are given by Wilhelms, 1990, p. 257–258, and in Hansen, 1991, p. 230–233.) When you are given a map to review, it takes priority over your own work! If an author so requests, the Map Coordinator will advise him/her how to respond to the reviews, particularly for the author's first VMAP map. Next, the USGS editor will check all material for consistency (internal and external) and for correct English, format, and style. The author will be responsible for producing the revised copies; the final copy, which the drafter will use, is known as the mill copy. It includes the brownline, a neat colored paper copy of the brownline (these two should be consistent), a colored correlation chart, any map overlays, illustration and figure originals, an electronic copy of the map text information on floppy disk, and hard copy of this text. USGS maps require "Author's Check List for Plates, Figures, and Photographs" for each illustration (reproduced in STA7, p. 188–189); these forms serve as work orders for the map drafter. Finally, the author will include a brief abstract (<75 words) for "New Publications of the Geological Survey" (follow *exactly* the format of the example in Hansen, 1991, p. 251).

Finally, the mill copy is submitted for approval by the Director of the USGS. Upon approval, an "I" number is assigned, the map is considered to be "in press," and the Office of Scientific Publications (OSP) of USGS in Flagstaff is given authorization to produce the map. The author or Map Coordinator may be questioned by OSP regarding line work, symbols, layout, unit colors, registration, geographic names, etc. A color proof will eventually be produced for checks by the author, USGS editor, and Map Coordinator.

One last note: a map cannot be cited in a USGS publication until it has been approved by the USGS Director and has an "I" number; if a mapper needs to refer to a colleague's work that has not yet received an "I" number, he/she should write "work in progress in the _____ quadrangle by Doakes (1994) suggests that..." or "map relations in the _____ quadrangle (Doakes, work in progress, 1995) indicate that..." These examples do not appear in Refences Cited, because they are not accessible to the reader.

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GLOSSARY OF RADAR TERMS

(modified from Ford and others, 1983, 1989; Sabins, 1987)

altimetry	Measurement of altitude
azimuth	Along-track direction of image acquisition
backscatter	Portion of transmitted microwave energy returned to the radar antenna to create a radar image
backscatter cross-section	The radar backscatter cross-section, or specific radar cross-section, σ_0 (ϕ), relates incident to backscattered power per unit area of the target surface, where ϕ is the polar incidence and scattering angle with respect to the mean normal
backslope	Slope that is inclined away from an incident radar beam
Bragg scattering	Reflections that are the result of radar waves superimposed on surface waves; the reflections reach a maximum when path-length differences between radar returns are an integral number of radar wavelengths
dielectric constant	Ratio of the electric flux density to the electric field; identical with dielectric permittivity
Doppler shift	Change in the observed frequency of electromagnetic waves caused by relative motion between source and detector
emissivity	The ratio, as a function of direction, of the thermal radiance of the radiator in each direction to that of a blackbody at the same temperature. The symbol for emissivity is ε.
foreslope	Slope that is inclined toward an incident radar beam
incidence angle	Angle between the incident radar beam at the ground and the normal to the ground surface at the point of incidence
layover	Geometric displacement of the top of a feature toward the near range on radar imagery
look direction	Direction in which pulses of microwave energy are transmitted from an imaging-radar antenna; normally at right angles to the line of flight of the imaging platform; Magellan observations made in both right- and left-look modes

"looks"	Number of independent radar observations summed for each resolution element
pixel	Square picture element of a digital image
radar	Radio detection and ranging
radiometer	A nonimaging device for quantitatively measuring radiant energy, especially thermal radiation
range	Across-track direction of image acquisition
reflectivity	The ability of a surface to reflect incident energy
resolution element	The minimum distance between two adjacent features on the ground, or the minimum size of a feature on the ground, that can be detected by an imaging system
rms (root mean square)	Statistical measure of magnitude; used for small-scale radar roughness of a surface
radar shadow	A dark area of no return on a radar image that extends in the far-range direction from an object on the terrain that intercepts the radar beam.
specular reflection	Mirrorlike reflection of a radar signal
synthetic-aperture radar (SAR)	A side-looking imaging system that uses the Doppler principle to sharpen the effective beamwidth of the antenna
synthetic-parallax	A stereo model produced digitally by introducing synthetic, stereo or artificial, stereo parallax (geometric distortion) into a monoscopic image as a function of the elevation in a digitally merged elevation model

APPENDIX A: VMAP PROGRAM PERSONNEL

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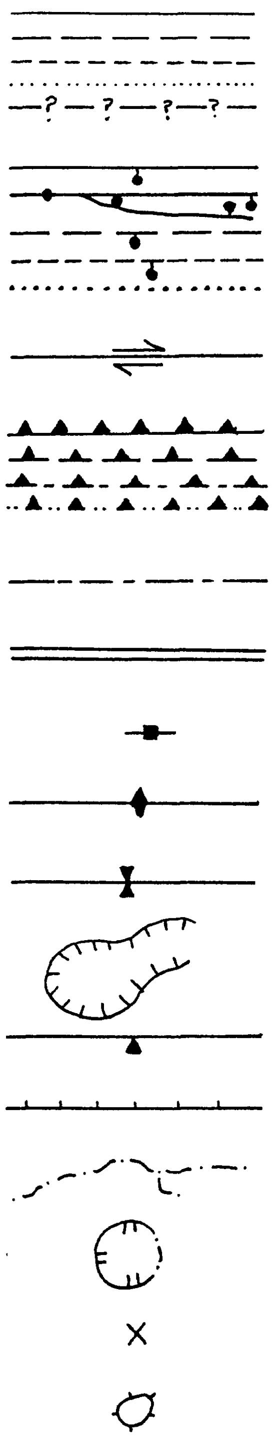
APPENDIX B: SAMPLES OF GEOLOGIC MAP SYMBOLS

[*Notes in brackets*]



Contact—Long dashed where approximately located; short dashed where indefinite, gradational, or inferred; dotted where concealed; queried where doubtful

Fault or graben—Long dashed where approximately located; short dashed where inferred or probable; dotted where concealed [must be concealed by overlying mapped deposits]; bar and ball on downthrown side

Fault—Arrows show relative horizontal movement

Thrust fault—Sawteeth on upper plate; dashed where approximately located; intermittent dashed where inferred; dotted where concealed

Fault or lineament—Origin uncertain

Tectonic lineament [Used on small-scale tectonic maps]

Joint [Assumed to be vertical]

Ridge crest

Trough

Depression [Includes large volcanic craters]

Scarp—Barb points downslope, line at base

Flow scarp—Hachures on downslope side

Channel

Crater rim crest—Dotted where buried

Small shield [Less than 20 km across]

Large shield [More than 20 km across]

APPENDIX C: RULES AND CONVENTIONS FOR NAMING VENUSIAN FEATURES

The International Astronomical Union (IAU), through its Working Group for Planetary System Nomenclature (WGPSN), is the body that approves names proposed for planetary features. The IAU also makes rules and sets policy regarding planetary nomenclature. The United States is an adherent to the IAU, and we are therefore compelled to follow its dictates in naming planetary features.

Among those rules that apply to Venus are the general rules that persons for whom features are to be named must be well known and deceased for at least three years. Names of persons prominent in any living religion or political or military figures of the 19th and 20th Centuries are disallowed. Furthermore, persons of a specific national significance are not acceptable. These rules are designed to avoid disruptive controversy that could obstruct the naming process.

In addition, the IAU makes rules regarding the kind of names that will be given to different types of features (a list of the feature types approved for Venus that can be named is provided in Table C1). On Venus, craters and volcanic calderas (paterae) are named for women of history; craters less than 20 km in diameter are given female first names from various world cultures. Other types of features are named for mythological women (Table C2). Names proposed for Venusian features must be selected from the proper category; otherwise, they are likely to be rejected. Consideration must also be given to keeping the nomenclature international in scope; that is, we must try to find and apply names from as many nationalities as possible.

Name proposals should be submitted to the USGS in Flagstaff, as the Branch of Astrogeology has been charged by the IAU with the responsibility of maintaining a record of all planetary name requests, as well as managing, updating, and distributing data from the nomenclature master files. Once a specific name has been proposed for a feature, it must be reviewed by two different committees of the IAU. The proposal is then voted upon by the WGPSN at their annual meeting. Once a name has been approved by the WGPSN, it is considered to have "provisional" status. Provisional names may be used in publication, but their provisonal status must somehow be indicated in the publication. (Provisional names on USGS maps are indicated by an asterisk.) The General Assembly of the IAU, which meets triannually, gives final approval to feature names.

Because the naming process is a lengthy one, it behooves mappers to make requests for feature names at the earliest possible time. As base maps become available, ozalid copies will be sent to Venus geologic mappers. Investigators will be asked to identify any unnamed features that they would like to have named. Mappers may propose names themselves, or a feature may be named by the nomenclature representative at USGS (see Appendix A).

Table C1. Feature types approved for use on Venus

FEATURE(S)	DESCRIPTION
Chasma, Chasmata	Canyon
Colles[1]	Small hills or knobs
Corona, Coronae	Ovoid–shaped feature
Crater, Craters	Bowl–shaped depression; impact crater
Dorsum, Dorsa	Ridge
Fluctus, Fluctūs	Flow terrain
Fossa, Fossae	Long, narrow, shallow depression
Linea, Lineae	Elongate marking
Mons, Montes	Mountain
Patera, Paterae	Shallow crater; scalloped, complex edge
Planitia, Planitiae	Low plain
Planum, Plana	Plateau or high plain
Regio, Regiones	Region
Rupes, Rupēs	Scarp
Terra, Terrae	Extensive land mass
Tessera, Tesserae	Tile; polygonal ground
Tholus, Tholi	Small domical mountain or hill
Vallis, Valles	Valley

[1]Used only in plural

Table C2. Categories for naming features on Venus

Feature	Source of name
Chasmata	Goddesses of hunt; Moon goddesses
Colles	Miscellaneous goddesses
Coronae	Fertility goddesses
Craters	Famous women; <20 km, female first names
Dorsa	Sky goddesses
Fluctūs	Goddess, miscellaneous
Fossae	Goddesses of war
Lineae	Goddesses of war
Montes	Goddesses, miscellaneous
Paterae	Famous women
Planitiae	Mythological heroines
Planum	Goddesses of prosperity
Regiones	Giantesses, Titanesses
Rupēs	Goddesses of hearth and home
Tesserae	Goddesses of fate or fortune
Terrae	Goddesses of love
Valles	Word for Venus in various world languages

APPENDIX D: FORMAT INSTRUCTIONS FOR TEXT AND EXPLANATIONS

Headings and Head Notes

Within the description of map units and text, headings are divided into orders—major headings (**INTRODUCTION, PHYSIOGRAPHIC SETTING, STRATIGRAPHY, STRUCTURAL HISTORY, REFERENCES CITED, DESCRIPTION OF MAP UNITS, etc.**) are first–order centered headings and further subdivisions are second order and third order.

Type, centered:

FIRST–ORDER HEADINGS ALL CAPS AND BOLD
SECOND–ORDER HEADINGS ALL CAPS BUT NOT BOLD
Third–order headings initial cap and lowercase and not bold

[Headnotes under centered headings are enclosed in square brackets, extend across entire column width (except centered if only one or two lines long), are not indented, and have no final period]

Map Units and Symbols in DOMU

Type all map unit names at first mention in lowercase and bold; follow by two hyphens. Begin the descriptive material with a capital letter. Do not put a period at the end of the last line of the description of each unit and do not divide the description into paragraphs. Start the name of each first–rank map unit about ten spaces to the right of the first letter of the map unit symbol.

First rank—"Left margin"
  Second rank—Indent two spaces
    Third rank—Indent four spaces
        Fourth rank—Indent eight spaces

All overruns of all ranks—Indent six spaces if more than two ranks are used, four spaces for two ranks, and two spaces for one rank.

Use the same format for symbols (such as contact, fault, etc.) as for map units. On a geologic map, such symbols are explained following the description of map units and a break of about four blank lines but no separate heading.

Example of map explanation. The sample explanation on the following pages demonstrates the application of the above rules (text modified from a Mars map being prepared by S.L. Rotto and K.L. Tanaka). It is made much narrower than an actual explanation to allow room for marginal notes. Note that it is followed by a corresponding correlation chart.

NOTE: This sample is for example purposes only; much of it is out of context.

Headnote
- Square brackets
- If three or more lines, run across entire column width, including symbols
- Centered if only one or two lines
- No final period

First-order centered heading
- All caps
- Bold
- Center over entire column width, including symbols

DESCRIPTION OF MAP UNITS

Place here your most significant information that applies to all units

[Map units distinguished and interpreted on basis of morphology, texture, albedo, and stratigraphic position. Although most map units are rock materials, some channel floors are also considered units in order to highlight erosional events that formed them]

Use telegraphic style! (Incomplete sentences o.k.)

LOWLAND TERRAIN MATERIALS

Chryse assemblage

First-rank unit
- Caps and lowercase
- Bold
- No indent of first line

Basin materials--Form lowland plains below mouths of outflow channels; interpreted to consist of sediments derived from outflow channels and possibly volcanic and eolian deposits. Contacts between basin units generally gradational

Interpretation and other general statements here may obviate need for adding them to subunits below (if they apply to all subunits)

Second-rank unit
- Caps and lowercase
- Bold
- 2-space indent of first line

No final period

cr **Subdued ridged unit**--Plains marked by subdued wrinkle ridges and cut by small outflow channels. *Interpretation:* Ridged plains material partly resurfaced by outflow erosion and deposition

Overruns indented 6 spaces for all ranks

Left margin at least 1"

Right margin at least 1"
Do not justify

Allow about 10 spaces; some letter symbols may be as long as 5 spaces

cc **Complex unit**--Characterized by one or more of the following: (1) hummocky topography; (2) small knobs (some superposed on mesas); (3) sinuous depressions about 10 km wide and tens of kilometers long; (4) sinuous ridges less than 1 km wide, some of which are medial in sinuous depressions or connect knobs; (5) narrow, curvilinear, northeast-trending grooves; and (6) several mostly buried crater rims. Unit gradational with smooth and grooved basin materials. *Interpretation:* Relatively thick lacustrine deposits from most recent flooding. Various features result of fluvial or glacial processes (or both) and compaction of sediments

Write out "kilometers" where not preceded by numerals

Note clear separation of observations and interpretation

Use this wording instead of "and/or" (which USGS doesn't permit)

cu **Undivided unit**--Material of Chryse assemblage occurring where image resolution does not permit discrimination of individual units

Text
- Closed up to hyphens
- Following hyphens
  -begins with cap letter
  -not bold

First-rank unit

Knobby materials--Interpreted as basin sediments and perhaps lava flows that embay knobs of older degraded plateau material

Second-rank unit

ck **Younger knobby material**--Forms knobby plains. Cut by lowermost Ares Vallis; gradational with older knobby material; embays mouth of Mawrth Vallis

Third-rank units
- Caps and lowercase
- Bold
- 4-space indentation of first line

cku **Upper unit**--Found only in upper reaches of Kasei Valles in southwest quadrant of map area

ckl **Lower unit**--Locally underlies upper unit but most exposures found in lower reaches of Kasei Valles in north-central part of map area

Describe relations of units after last (oldest) unit is identified

cko **Older knobby material**--Closely spaced groups of knobs on high, undulatory plains along highland-lowland boundary (fig. 1). Typical exposures at lat 14.4°N., long 172° (Viking frame 639A12)

Use "type area" only when formally proposing geol. name (note also style of map coordinates)

All geographic features mentioned should be located (1) on main map, (2) in a figure that is referenced here, <u>or</u> (3) in words earlier in text

HIGHLAND TERRAIN MATERIALS

Tharsis assemblage

[Lava flows originating in Tharsis region]

Tharsis Montes Formation--

Easternmost flows of large shields of Tharsis Montes; exposed in western part of map area

t5 **Member 5**--Marked by elongate, high-albedo flow lobes with distinct margins; craters rare. Correlative with member 3 of Tharsis Montes Formation as mapped by Doakes (1983)

Capital "F" in "Formation" because it is formal geol. name

Give locations of outcrop areas if too small for reader to locate quickly (note use of "map area," not "map")

Avoid use of "with" where possible. Here, substitute "having"

This is most visible location for information on correlation

Lowercase "m" in "member" because it is informal geol. name (Note that "member 3" is written out, not referred to by symbol t3)

NOTE: In explanation of map symbols, overruns have same indentation as overruns in Description of Map Units (6 spaces in this example).

Sample Correlation Chart

The following correlation chart corresponds to the above description of map units: