to lower apoapsis. If this proves feasible, then a valuable set of high-resolution, global gravity data may be obtained. In addition, much higher resolution radar imaging data may be achievable.

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An Overview of Venus Geology

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The Magellan spacecraft is producing comprehensive image and altimetry data for the planet Venus. Initial geologic mapping of the planet reveals a surface dominated by volcanic plains and characterized by extensive volcanism and tectonic deformation. Geologic and geomorphologic units include plains terrains, tectonic terrains, and surficial material units. Understanding the origin of these units and the relation between them is an ongoing task of the Magellan team.

The scientific goals of the Magellan mission are to improve the knowledge of the geological history of Venus by analysis of the surface morphology and electrical properties and the processes that control them (including tectonic and volcanic histories and evidence for climates different from the present regime) and to improve the knowledge of the geophysics of Venus, principally its density distribution and interior dynamics. In order to accomplish these goals the experimental objectives of the mission are to acquire a global, high spatial resolution radar image of the surface, produce maps of topographic and radar scattering characteristics, and to refine the global gravity field with the use of spacecraft tracking data. With these observations a number of first-order questions on the geologic history and the nature of the geologic processes that have shaped the planet can be addressed (*1*). The data reported in this issue are from the first 6 weeks of Magellan mapping and thus based on coverage of less than 15% of the planet (*2*). Details of the imaging and altimetry data processing are provided elsewhere (*3*).

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In this report, we present an overview of the nature and timing of geological processes in the areas imaged to date. In general, Venus is valuable as a laboratory for testing geologic hypotheses because it lacks a hydrosphere and hence primary features produced by geologic processes have not been extensively eroded (*4*). The dominant processes have been volcanism (*5*) and tectonism (*6*), and it is clear from the relatively low average density of impact craters on the surface that these processes were extremely active during the planet's geologically recent past (*7*).

Soviet and U.S. exploration of Venus began with the U.S. Mariner 2 spacecraft in 1962. In the 1970s, seven Venera landers provided data on the physical and chemical nature of the surface (*8*). Earth-based radar observations of Venus have been made by radiotelescopes at Goldstone, California, and Arecibo, Puerto Rico, and orbiters (Pioneer Venus and Veneras 15 and 16) have provided both radar images and altimetry of the Venus surface. The earliest observations revealed that Venus has fixed features, allowed an estimate of the 243-day retrograde rotation, and provided estimates of surface temperature.

The small-scale morphology of the surface of Venus has been characterized on the basis of lander images provided by Venera 9, 10, 13, and 14 (*8, 9*). Venera 9 showed a steep (~30°) slope of a hill densely covered by decimeter-size plate-like rock fragments and some loose soil in between. Venera 10, 13, and 14 have shown small areas of plains in which the surface is dominated by low-standing, flat-topped outcrops of bedded rocks with variable amounts of loose soil material in local lows.

The chemical composition of surface material has been determined at seven locations (*10, 11*). All of them except the Venera 9 site are in the plains near the equator. Two measurement techniques were used: gamma-ray spectroscopy, which determines the content of K, U, and Th in the surface layer beneath the lander (Venera 8, 9, and 10 and Vega 1 and 2), and x-ray fluorescence, which determines the content of Si, Ti, Al, Fe, Mn, Mg, Ca, K, S, and Cl in a centimeter-size sample taken by drilling beneath the lander (Venera 13 and 14 and Vega 2). At five of the seven landing sites (Venera 9, 10 and 14 and Vega 1 and 2) the surface material is similar in composition to tholeiitic basalt. At the Venera 13 landing site the surface material is similar in composition to terrestrial subalkaline basalt. At the Venera 8 landing site the surface material is similar in composition to alkaline basalts, shoshonites, and syenites. Recently Nikolayeva (*11*) concluded that the material has a quartz monzonite–quartz syenite affinity that resembles parts of Earth's continental crust. The color of the surface material is dark and slightly reddish (*12*). Most of the data (including bedded rocks) indicate that the surface material was friable and porous. Bearing capacity was estimated at 40 to 50 Mg/m^2, and density at 1.4 to 1.5 Mg/m^3. The only exception are data from the gamma-densitometer of Venera 10, which indicated that the density of the rock at the site is as high as 2.8 Mg/m^3 (*9*).

The near-surface temperature (reduced to the topographic datum) measured by Venera and Vega landers was 475 K, the pressure was 90 bar, and the near-surface wind velocity was less than 1 m s^{-1}. The wind was strong enough to gradually decrease the size of a clump of soil thrown onto the supporting ring of the probe during the landing event (*3*).

Goldstone and Arecibo images allowed geologic features on Venus to be studied at a resolution of 1 to 2 km in several areas (*14*). Rift zones were discovered in Beta Regio (*15*), and mountain ranges in Ishtar Terra (*16*) (Fig. 1). Recent Arecibo images of the southern hemisphere of Venus permitted identification of complexly deformed terrain in Alpha Regio (*17*). A major circular feature, Heng-o, identified with Goldstone data (*18*) may be related to hot spot activity (*19*). In general, these data revealed that the Venus surface has a complex and spatially varying tectonic and volcanic history.

In 1978, the Pioneer Venus spacecraft returned radar images from about 40°N to

10°S and altimetry data from 78°N to 63°S. Pioneer Venus radar images (resolution about 30 km) and altimetry data (footprint size about 100 km, accuracy about 100 m) showed the distribution of three physiographic provinces—highlands (about 8% of the surface), rolling plains (65% of the surface), and lowlands (27% of the surface) (*20, 21*) (Fig. 1). Of the highlands, Ishtar Terra was interpreted as an uplifted plateau and Aphrodite as a complex, degraded, tectonically disrupted region. Complex ridge and trough regions east of Ishtar Terra, in southern Aphrodite Terra and between Aphrodite and Beta Regio were interpreted as resulting from large-scale crustal motions (*20*). Gravity data showed that long wavelength topography and gravity are strongly correlated in contrast to the situation on Earth (*22*).

Venera 15 and 16 mapped Venus in 1983 and 1984, returning radar images and altimetry of the northern quarter of the planet at a resolution of 1 to 2 km, an incidence angle ~10°, a footprint of 40 to 50 km, and an altitude accuracy of ±50 m. A number of features and terrains were distinguished and mapped (*23, 24*) including several varieties of plains, interpreted to be of volcanic origin. Several tectonic features were recognized, including domical uplifts, low ridge belts on plains, and high mountain belts, heavily deformed areas called tesserae, and peculiar ring-like features called coronae. The latter two types of features had not been recognized on other planetary bodies. Volcanic constructs of various sizes, large calderas, enigmatic arachnoids (volcanic features surrounded by a network of lineaments), probably formed by combinations of volcanic and tectonic processes. Impact craters were also identified.

Consideration of this set of terrains and features led to the conclusion that Venus is dominated by basaltic volcanism and tectonic deformation. The abundance of large impact craters in the area studied by Venera 15 and 16 is comparable with that on terrestrial continental cratons. This relation implies that the crater retention age on Venus is not less than about 400 million years (*24, 25*) and that over that time volcanism and deformation have been the dominant resurfacing mechanisms. No reliable evidence of global endogenic activity similar to Earth's plate tectonics was found (*26*).

Magellan data indicate that the surface of the planet is dominated by geomorphologically complex plains regions that have been affected by multiple episodes of tectonic and volcanic activity. The surface of Venus appears to be relatively young geologically and quite active. Highland terrains show geomorphologically diverse appearances, possibly indicating multiple origins and modes of evolution. Understanding the stratigraphy of the planet will be a major challenge because of the low density of impact craters, and the complex nature of some regions, such as tesserae.

Magellan images have confirmed the existence of extensive, and in many regions, intensive tectonic deformation (*5*). Linear belts of mountains with a banded ridge and trough aspect are a prominent tectonic element on Venus, a characteristic shared with Earth but no other terrestrial planet. These tectonic patterns on both planets indicate that there is a relation between interior dynamics and surface deformation, but no Earth-like plate tectonic patterns have been delineated from the Magellan data. Evidence to date from crater morphology and surface modification supports the conclusion that rates of resurfacing from volcanic and tectonic activity are low compared with Earth.

New findings include the presence of abundant extensional features in the mountains. These may be related to passive pro-

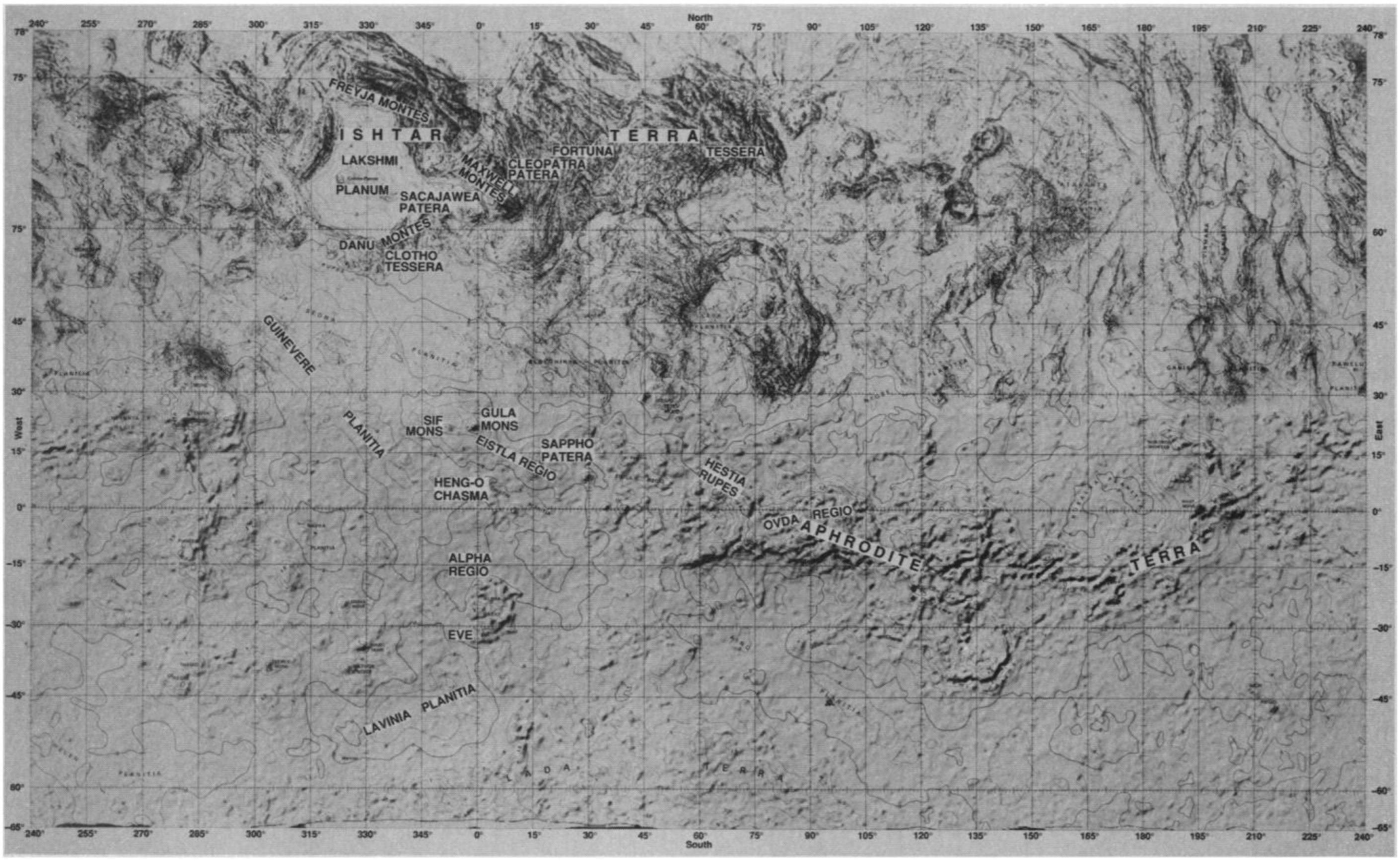

Fig. 1. This map combines two Venus radar and altimetry data sets. An airbrushed version of the Venera 15–16 radar datasets extends from 78°N to approximately 30°N, the southern limit of Venera coverage. The remainder of the map is composed of a shaded relief version of Pioneer Venus altimetry.

cesses of relaxation rather than providing clues to the origin of the mountains. The plains are fractured in nearly all regions, except for the most recent surfaces. Evidence for shear deformation has also been found; this type of deformation is also shared with Earth but is rare on other terrestrial planets.

Basaltic volcanism is a dominant process on terrestrial planet surfaces. Venus plains show widespread evidence of volcanic flooding and abundant small shield volcanoes. Study of volcanism on Venus should improve our understanding of volcanic processes on Earth, such as the origin and evolution of flood basalts.

Some new volcanic types have been found on Venus (*6*). New, for Venus at least, are circular, flattened domes up to 30 km in diameter and nearly 1 km high. These domes typically have small summit pits and generally occur in lines of overlapping individual domes. Channels associated with lava extrusion and emplacement of plains lavas are not uncommon on Earth. The lava channels on Venus provide conduits for lava and may extend tens to hundreds of kilometers in length with remarkably constant 1 to 2 km widths. The mean age of the surface inferred from the abundance of impact craters is a few hundred million to 1 billion years. There are few impact craters modified by volcanism (*7*), but there are large areas without visible craters. These characteristics imply that volcanic resurfacing is locally efficient but episodic and specifically heterogeneous (*7*).

Magellan has confirmed that most of the features interpreted as impact craters from Venera and Arecibo data are of impact origin (*5*). The areal density of impact craters is the same as observed by Venera investigators. However, the ten times as high resolution of the Magellan images has revealed impact craters as small as about 3 km in diameter, whereas Venera detected craters no smaller

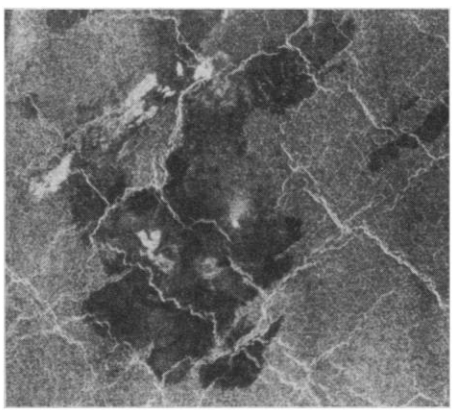

Fig. 2. Reticulate plains unit. These plains, centered at −1.8°S, 336.5°E in Guinevere Planitia, are characterized by broadly spaced reticulate lineaments. The radar-dark flows overlie, and are thus younger than the underlying reticulate plains. This image is ~90 km across.

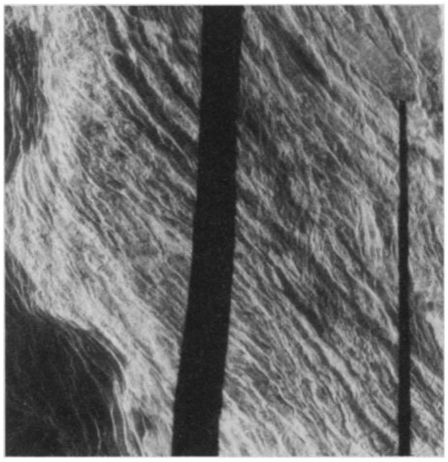

Fig. 3. Ridged terrain located in Maxwell Montes. The image is centered at 64.5°N latitude, 3°E longitude. The image is ~310 km across.

than about 8 km. Magellan data confirm the atmosphere limits the formation of small impact craters by inducing the breakup of small projectiles in the atmosphere. Radar-dark zones seen around impact craters are interpreted to be related to the impact process.

A newly discovered phenomenon of impact is the presence of outflow materials and channels from within ejecta blankets. Such channels may be formed by a flow of low-viscosity melt generated during impact, or sediment-charged gases resembling nuee ardentes. Large U-shaped dark surficial deposits extend hundreds of kilometers to the west of some of the larger craters (*4*). The consistently westward orientation of these features suggests that the east-to-west flow of the general atmospheric circulation, the so-called super-rotation, was involved in formation of the deposits. Many craters and their radar-bright ejecta are outlined by dark zones that extend out a few crater diameters. Many dark areas, however, have no associated crater and may indicate that the incoming projectile completely broke up.

Magellan images reveal wind streaks in many regions, typically in the lee of topographic obstacles (*4*). Global mapping of these streaks might reveal the general pattern of atmospheric circulation at the surface. Many steep massifs show evidence of mass wasting, a persistent but not very effective mechanism of surface modification. The occurrence of low emissivity and highly reflective surface material, as seen in the Pioneer Venus data, has been confirmed by Magellan data (*27*). Analysis of the temperature and pressure conditions of these surfaces should help identify the possible stable mineral phases responsible for this phenomenon.

Analysis of Magellan radar images indicates that morphologic units defined in Venera and Arecibo radar images have complex and variable morphology.

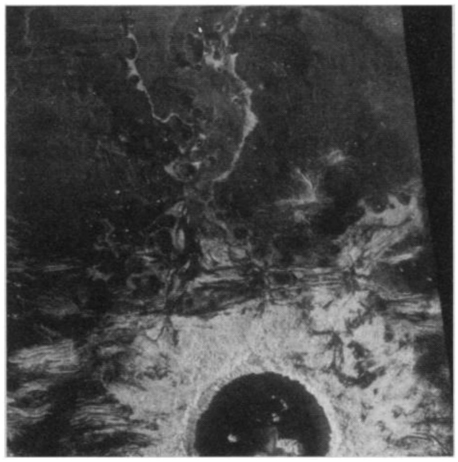

Fig. 4. This Magellan mosaic shows a bright lobate surficial material unit associated with the crater Aglaonice, a 62.7 km-diameter crater at 26.5°S, 339.9°E. The deposit surrounds several small domes of probable volcanic origin.

Plains terrains are planar, areally extensive regions and are identified dominantly by surface morphology and topography. (i) Smooth plains have a featureless appearance, no discernible volcanic flow units, and few domical hills or linear features [figure 10 in (*5*)]. These plains are formed by volcanic flooding or by coalescing of volcanic shields undetectable in high-incidence-angle radar images. In either case, the lack of lateral variations in signature suggests that the surface has been homogenized by weathering, erosion, and burial (*4*). (ii) Reticulate plains are characterized by one or more sets of sinuous, radar-bright lineaments unresolvable as ridges or grooves (Fig. 2). These linear features tend to be spaced >5 km apart. Reticulate plains are interpreted to be volcanic flows or shields that have embayed underlying structure or have been also deformed, or both. (iii) Gridded plains are characterized by intersecting orthogonal sets of radar-bright lineaments, typically extending for hundreds of kilometers with regular spacing [figure 3 in (*5*)]. Linear features lack the sinuosity of features in Reticulate plains and tend to be spaced closer (<5 km), and have been affected by complex tectonic deformation (*5*). (iv) Lobate plains have overlapping lobate regions of variable backscatter strength that extend for tens to hundreds of kilometers [figure 18A in (*6*)] and few or no linear features; fractures (if present) and topography tend to control emplacement of plains materials. Lobate plains represent coalescing volcanic flows and flow complexes.

Tectonic terrains are also identified by surface morphology and topography. (i) Cross-lineated terrain units have moderately high topographic relief and are areally extensive. The terrain is characterized by intersecting sets of lineaments generally unresolvable as ridges or grooves [figure 24C in (*5*)]. This unit is a subdivision of larger, more complex geomorphologic regions called tesserae (*23, 26*) and has formed by complex deformation (*5*). (ii) Ridged terrain occurs at high elevations (>1 km above mean planetary radius) and is characterized by long (>100 km) ridges and valleys that are commonly cut by shorter grooves and ridges. Both linear and equidimensional ridged terrains are seen (Fig. 3). The mountains are interpreted to have formed from compressional deformation, followed in some areas by extension (*5*). Two types of linear belts, typically 30 to 50 km wide (*23*), have been identified on the basis of the dominant tectonic feature. (iii) Ridge belts, a large group of which are found in Lavinia Planitia [figure 6 in (*5*)] are commonly cut by grooves. Ridges tend to lie in belts of high radar cross section that is attributed to increased roughness resulting from tectonic disruption. Ridge belts tend to extend for hundreds of kilometers and to have relief of 1 km or less. They are interpreted to be compressional in origin; some are cut by later episodes of extensional deformation (*5*). (iv) Groove belts are belts of linear structures dominated by grooves typically spaced 5 to 20 km apart [figure 37C in (*5*)]. The belts are associated with areas of raised topographic relief, typically higher than in ridge belts. The grooves are interpreted to be local extensional features over areas of compression (*5*).

Magellan data have revealed a number of surficial material units not previously identified, with the exception of crater materials: (i) Crater materials are deposits located within and surrounding craters and are characterized by high radar cross sections [figure 1A in (*7*)]. Material surrounding craters generally has lobate boundaries and a hummocky appearance, and is interpreted to be of impact origin (*7*). (ii) Channel materials are generally sinuous with a low radar backscatter cross section. Channels are 1 to 3 km across, are located in plains and highland regions [figure 17A in (*6*)], and are interpreted to be lava channels or sinuous rilles (*6*). (iii) Bright lobate surficial materials have variable radar cross section and are contiguous with crater materials. They extend from 50 to 200 km; their emplacement tends to be topographically controlled (Fig. 4). These units are interpreted to result from outflow of highly fluid material, probably volcanic in origin, caused by the cratering process (*7*). (iv) Bright material (high radar cross section) appears to be contiguous with ridges or small domical hills in many areas or appears as long (>100 km) linear units. Some bright areas have a feathered appearance [figure 8 in (*4*)] and are interpreted to be regions of increased surface roughness created by deposition or removal of material by wind. (v) Many regions contain circular or elongate, dark diffuse materials [figures 8 in (*4*) and 6C in (*7*)]. Dark material is interpreted to be areas of increased smoothness due to deposition of fine material. (vi) Linear faceted material occurs in groups of lineations, typically extending for <100 km [figure 8 in (*4*)]. This unit may represent sand dunes (*4*).

Initial analysis of Magellan data has revealed the complex nature of volcanic and tectonic processes that have affected the planet's surface. Unexpected initial results include the great variety of volcanic landforms, the intensity of tectonic processes, and the outflow features associated with impact craters. Further analysis and mapping to obtain a global understanding of the geologic history of Venus, and detailed comparisons with geologic processes on other planets (including Earth) are ongoing.

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Fundamental Issues in the Geology and Geophysics of Venus

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A number of important and currently unresolved issues in the global geology and geophysics of Venus will be addressable with the radar imaging, altimetry, and gravity measurements now forthcoming from the Magellan mission. Among these are the global volcanic flux and the rate of formation of new crust; the global heat flux and its regional variations; the relative importance of localized hot spots and linear centers of crustal spreading to crustal formation and tectonics; and the planform of mantle convection on Venus and the nature of the interactions among interior convective flow, near-surface deformation, and magmatism.

One of three distinct mechanisms dominates global heat transport across the lithosphere (*1*) of solid planets and satellites: (i) recycling of lithospheric plates (as on Earth), (ii) hot-spot volcanism (as on Io), or (iii) simple conduction through a globally continuous lithospheric shell (as on the smaller terrestrial planets). The mechanism of lithospheric heat transport on a planet is fundamentally linked to its tectonic and volcanic evolution. The dominant lithospheric heat transport mechanism on Venus—the planet most sim-

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