SKY & TELESCOPE

Venus Globe

R. Stephen Saunders

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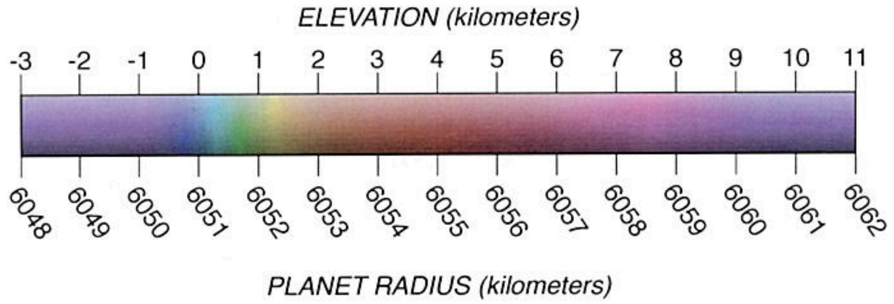
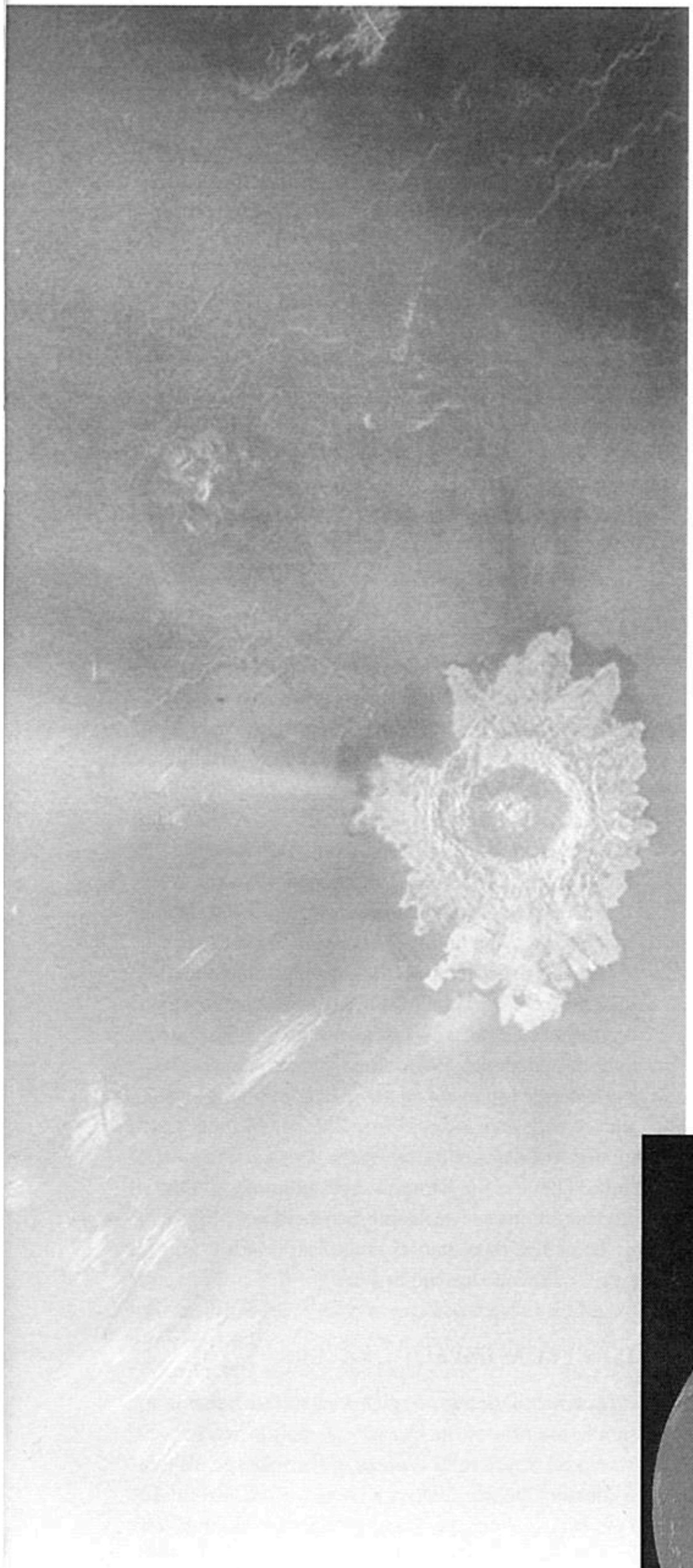


SCALE: Approximately 1:40,000,000
(1 mm = 40km, 1 inch = 625 mi)

THIS GLOBE SHOWS the surface of Venus as revealed by more than a decade of radar imaging that culminated in the 1990-1994 Magellan mission. The Magellan spacecraft mapped more than 98% of Venus at a resolution of about 100 meters; the effective resolution of this globe is about 5 km (3mi).

A mosaic of the Magellan images (most with illumination from the west) forms the map base. Gaps in the Magellan coverage are filled with images from the Soviet Venera 15 and 16 spacecraft in the northern quarter of the planet, with radar images from Arecibo Observatory (Puerto Rico) in a region centered roughly on 0° latitude , and with a neutral tone elsewhere (primarily near the south pole). The composite image is processed to improve contrast and to emphasize small features. Colors indicate elevation; gaps in the elevation data from the Magellan radar altimeter were filled with altimetry from the Venera 15/16 and the U.S. Pioneer Venus missions.

The Magellan mission was managed for the National Aeronautics and Space Administration by the Jet Propulsion Laboratory (JPL), Pasadena, CA. Data was processed by the JPL, the Massachusetts Institute of Technology, Cambridge, MA, and the U.S. Geological Survey, Flagstaff AZ. The Sky & Telescope Venus Globe was manufactured by Replogle Globes, Inc., and produced by Sky & Telescope Media, LLC., 90 Sherman Street, Cambridge, MA 02140, U.S.A.; www.SkyandTelescope.com



Adivar crater on Venus, as seen in a radar image from the Magellan orbiter.

Venus

R. Stephen Saunders

In the past few years, planetary scientists have studied in detail a world that can perhaps teach us a great deal about Earth. Venus was expected to be like our planet in many ways. It is nearly as large as Earth (*Figure 1*), and everything we know about Venus suggests that it is made of the same stuff as Earth and in about the same proportions — except for one key ingredient. Venus is dry. It has almost no water. This lack of water may explain why Venus is, in fact, very *different* from Earth and apparently has always been so.

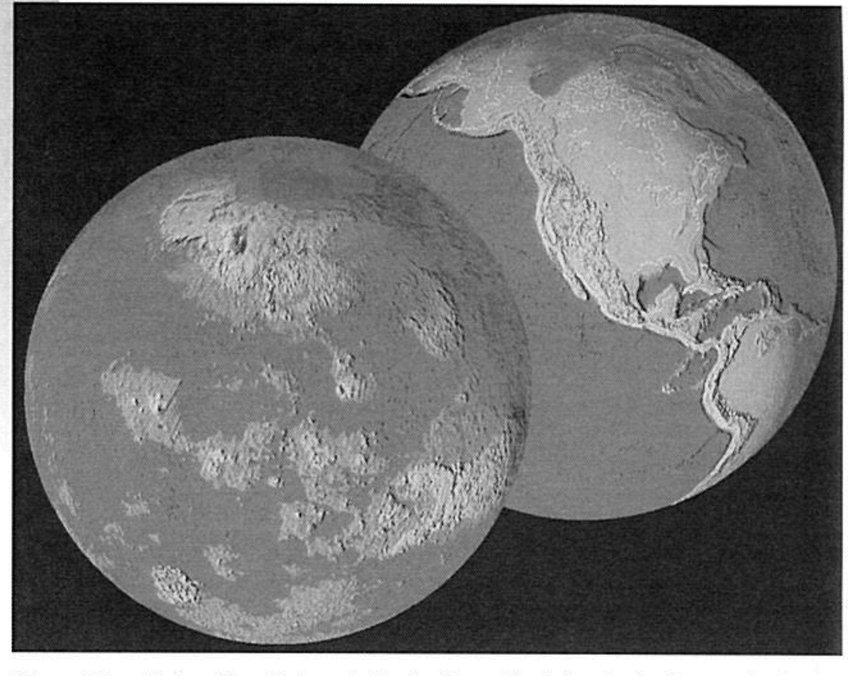


Figure 1. Even before Magellan's arrival, scientists realized that the landscape of Venus (left) was dominated by vast plains and lowlands, with few landmasses comparable to Earth's continents (right).

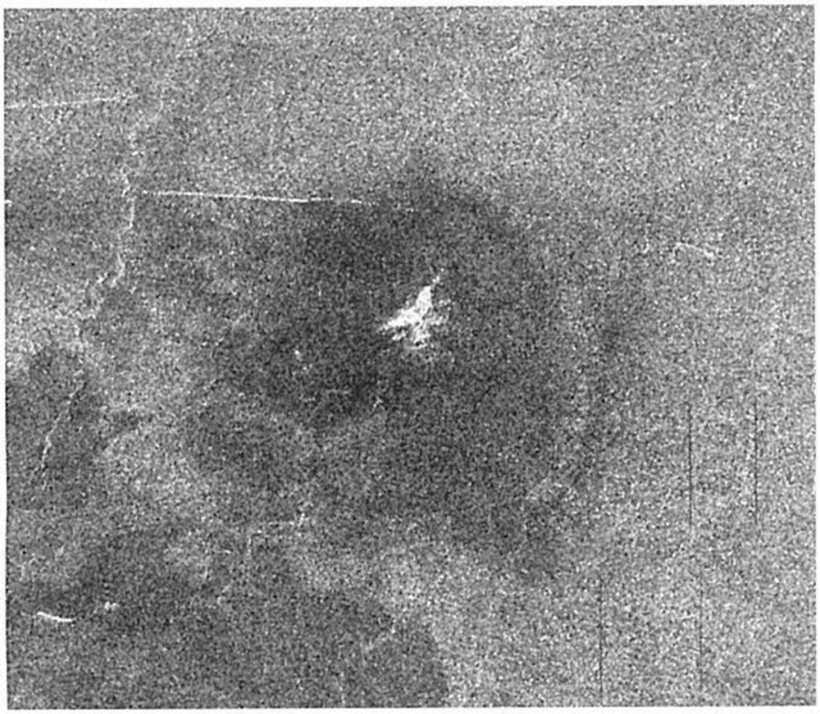


Figure 2. **This image covers an area of approximately 50 km by 60 km and is located in the Lakshmi region of Venus at 47° north latitude and 334° east longitude. The dark circular region and associated central bright feature are thought to be the remnants of a meteoroid smaller than the size necessary to create an impact crater.**

The virtual absence of water explains, for example, why Venus has a dense atmosphere made up mostly of carbon dioxide (CO_2). If Venus had ever had oceans, that carbon dioxide would have formed limestone and other carbon-bearing rocks. As much carbon dioxide has come out of Earth's interior, mostly in volcanic eruptions, as we find in the entire Venus atmosphere. However, our oceans remove CO_2 from the atmosphere and keep Earth habitable. Because carbon dioxide is an excellent greenhouse gas, sunlight that penetrates into the Venusian atmosphere stays as heat, and today the planet's surface is about 750° K.

We have known for decades that Venus was a dry planet. However, the full significance of that fact, especially with regard to surface processes, could not be imagined because the clouds and haze in the planet's dense atmosphere shield its landscape from our view. Fortunately, we can see through to the surface using radar imaging. Our first crude identifications of Venusian surface features came in the 1960s, when powerful radio telescopes near Goldstone, California, and Arecibo, Puerto Rico, bounced radar pulses off the planet and analyzed the returning echo. In time this Earth-based technique matured and revealed many discrete features. However, it never did resolve the surface of Venus with enough detail to be geologically definitive.

Global-scale radar mapping of Venus began with NASA's Pioneer Venus mission in the late 1970s. This was followed in the mid-1980s by Veneras 15 and 16, twin spacecraft from the former Soviet Union that mapped much of the planet's northern hemisphere. The results from these missions established basic surface units distinguished on the basis of variations in radar properties, surface textures, topography, and morphology. True revelation, however, did not come until the arrival of the Magellan orbiter, which systematically mapped Venus from September 1992 to October 1994, when it plunged into the atmosphere. Magellan was in a polar orbit. Consequently, as Venus slowly rotated through its 243-day period beneath the spacecraft's radar gaze, the entire globe was eventually revealed.

Magellan imaged 98 percent of the planet's surface at a resolution of 120 to 300 m. The spacecraft carried a side-looking radar system that "illuminated" a narrow strip of surface with radio energy as the spacecraft moved along its orbit, then it recorded the reflected signal. Magellan's radar looked off to one side at an angle of 35°, compared to the 10° used by Veneras 15 and 16. This allowed us to distinguish terrains with rough textures fairly easily. Also on board was a second radar system that sent radar pulses straight down to continuously gauge the height of the topography below.

Regions that are bright in the reconstructed radar images have higher radar reflectivity. Such areas are often rougher than their surroundings on the scale of the radar's wavelength, a few centimeters to a few meters. Strong radar echoes come from rough-textured lava flows or the blocky surfaces surrounding impact craters. Sometimes terrain looks bright if tilted so it faces toward the spacecraft, like the side of a hill. In either case, more radio energy than average is reflected back to the spacecraft receiver. In some cases, particularly at the highest mountain elevations, strong radar reflectivity seems to indicate a kind of "shiny" terrain thought to contain a metal component with a high dielectric constant, such as pyrite (FeS) or iron oxides like magnetite (Fe_3O_4).

The Magellan radar images and altimetry readings have been painstakingly compiled into global maps that allow us to identify and map different terrain types and geologic units. The geologic characterizations extracted from Magellan data build upon the basic criteria established by the Pioneer Venus and Venera results. These, along with the application of such stratigraphic interpretations as overlapping and crosscutting relations, have helped us to obtain as much information on the chronology of rock sequences as possible.

SURPRISES FROM IMPACT CRATERS

One important clue to the age of a planetary surface is the number, size, and condition of the impact craters it bears. Impact craters are seen on all the solid surfaces of the solar system (see Chapter 6), formed by the infall of asteroids and comets at 20 to 30 km per second or more. Impact events are more or less random in time and space when viewed over millions of years. Thus the older the surface, the more craters it should have. Unfortunately, such crater counts only provide relative ages of the surfaces involved. For the Moon we have been able to put absolute numbers on the lunar time scale by dating the samples returned by the Apollo astronauts. On other worlds, however, there is great uncertainty in the absolute ages. In spite of such uncertainties, craters have been extremely useful in unraveling the sequence of geologic events on the Moon, Mars, and outer-planet satellites.

September 1992 was an exciting time for those awaiting the first global view of Venus. We already knew that the planet was cratered, thanks to the low-resolution radar images from the Arecibo and Goldstone radio telescopes on Earth and from the Veneras. As the first days of mapping progressed, the Magellan science team eagerly pored over the image "noodles," each one representing a piece of Venus 20 km wide and 15,000 km long. The first few images scrolled across several large impact craters.

After a few weeks of mapping, with about 10 percent of Venus revealed, a profound puzzle began to emerge. Volcanism dominated the surface. Lava flows and various kinds of volcanoes were everywhere. Faults and fractures crisscrossed the landscape. Wind streaks were abundant. All of these things were fascinating but not unexpected. The craters provided the big surprise. On the Earth, Moon and Mars, craters range from very fresh scars to barely visible, eroded circular ghosts. However, apparently little erosion had affected the Venusian craters. They all looked as if they had formed recently.

Further, as mapping proceeded, the craters appeared to be scattered randomly over the surface. Unlike the Moon or Mars, there were no highly cratered (ancient) regions intermixed with lightly cratered (younger) regions. All the surface appeared to be about the same age and geologically young. If we use the lunar chronology and crater densities as a guide, the average surface age of Venus could be no more than about 500 million years. We were seeing only the last 10 percent of Venus's geologic history recorded in its surface.

As it turned out, the impacts seen during the first month of mapping proved to be representative of the entire planet's crater population. No one has been able to demonstrate convincingly that the approximately 1,000 Venusian craters are distributed in any arrangement other than randomly scattered. They must truly represent an average time of accumulation of less than 500 million years, and as such they provide important constraints on the evolution of Venus — but in very unexpected ways.

The finding of a sparse, pristine, and randomly distributed crater population immediately led to an interesting scientific debate. One explanation is that volcanic eruptions destroy craters about as fast as they form, so that we will always see about the same number of craters on Venus. This is the "equilibrium hypothesis," or what some geologists call the uniformitarian model. Another interpretation is the "global-catastrophe hypothesis," according to which massive volcanic eruptions approximately 500 million years ago resurfaced the entire globe and thus erased all the craters that had formed earlier. Having been wiped clean, the surface again began to collect craters, and nothing much else happened geologically except for some faulting and a few large volcanoes.

Curiously, this debate about Venus echoes a debate among early geologists a couple of hundred years ago. The catastrophists believed that most of Earth's rocks formed over a short period of time in the Noachian floods, while the uniformitarianists held that "the present is the key to the past." In other words, geologic time was vast, and enormous surface modifications result from slow changes that we can see operating today. In that early historic debate, the uniformitarianists ultimately won out. For Venus, in the opinion of this writer, the catastrophe model will in time be judged more nearly correct than the equilibrium model.

Aside from their number and distribution, the craters themselves have proved very interesting. We anticipated that the dense atmosphere of Venus would shield the planet from small asteroidal and cometary debris, allowing only larger bodies to reach the surface. Magellan images show no intact craters less than about 3 km across. This means that no objects larger than about 30 m in diameter make it to the surface with enough of their initial velocity to produce a crater. Small objects either are destroyed by the atmosphere or are slowed so much that they simply fall onto the surface at low speed.

However, the craters' appearances were difficult to predict, and they show several intriguing characteristics. Even though the smallest meteoroids never reach the ground, the energy they dissipate during atmospheric passage apparently creates strong winds and shock waves that disrupt the surface, producing diffuse, radar-dark "splotches" (*Figure 2*). Sometimes the splotches have a bright center, apparently marking a cluster of small impacts, ejecta, and debris from the broken-up meteoroid. What caused these features? Since smooth surfaces generally appear

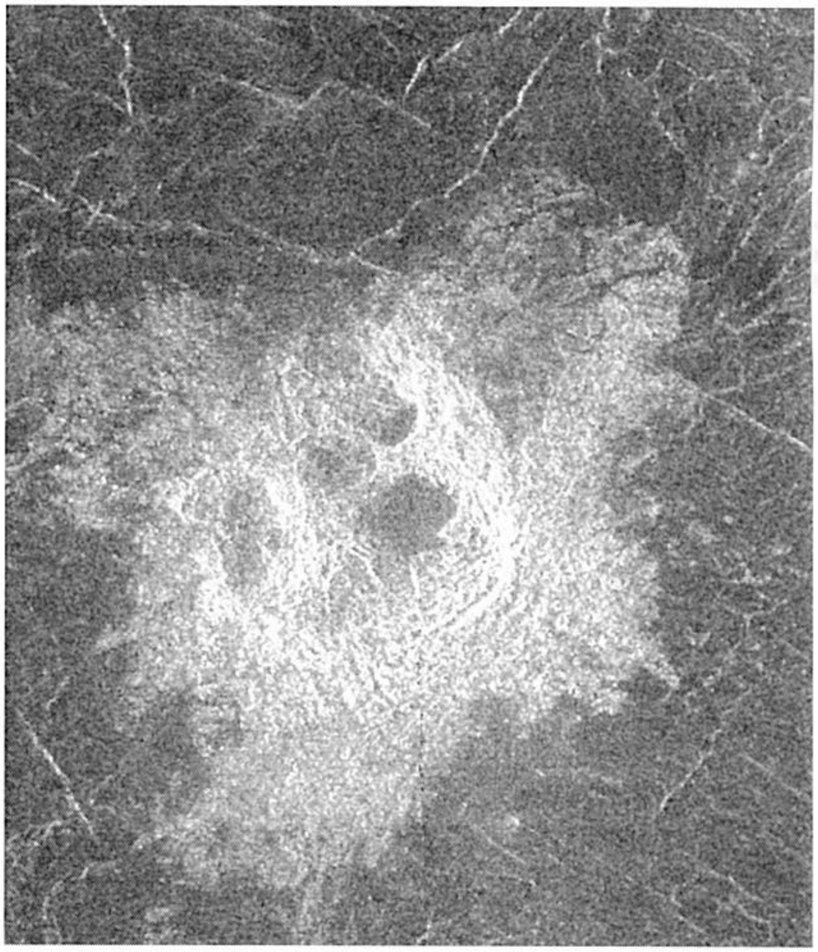


Figure 3. **The multiple crater Lillian, a 13.5-km-diameter crater in the Guinevere region of Venus (25.6 °N, 336.0°). This crater is actually a cluster of four separate craters whose rims touch or overlap.**

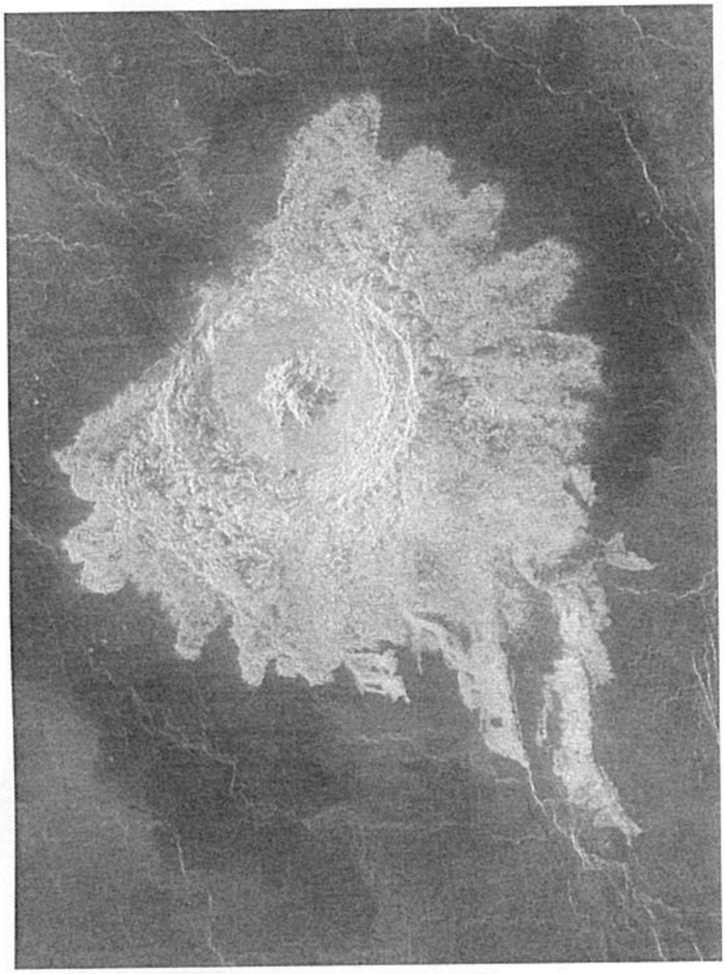


Figure 4. **The crater Aurelia is centered at 20.3° north latitude and 331.8° east longitude. With a diameter of 32 km, it displays a circular rim, terraced walls, and central peaks. Geologists are intrigued by how the radar-bright (rough) ejecta surrounding the crater creates an asymmetric pattern that indicates the impactor's incoming direction (from upper left).**

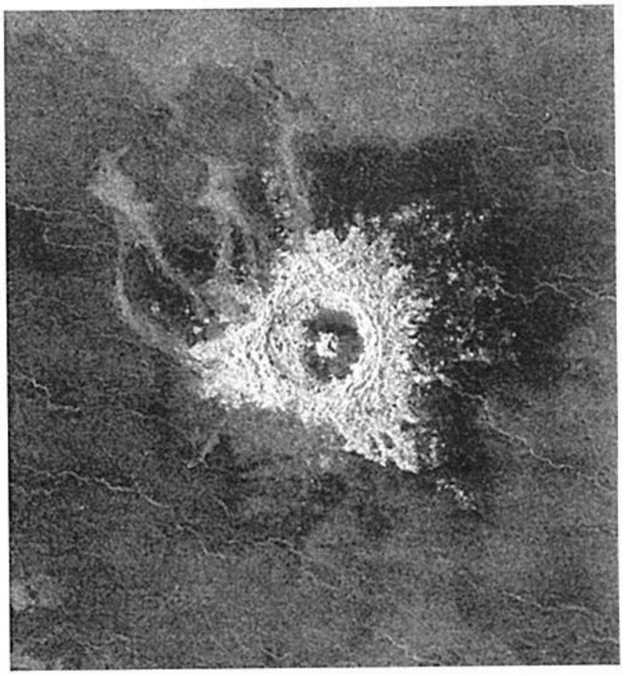


Figure 5. **Jeanne is a 19.5-km-wide impact crater located at 40.0° north latitude and 331.4° east longitude. The distinctive triangular shape of the ejecta indicates that the impacting body probably hit obliquely, traveling from southwest (lower right) to northeast.**

dark in a radar image, it could be that the meteoroid's atmospheric shock wave was energetic enough to pulverize and flatten the surface below. Another explanation is that the surface could be blanketed by a fine material that fell from the sky — the dusty remains of the original meteoroid. More than half of the impact craters on Venus have associated dark margins, and most of these are prominently located to the west of the crater's center. This drifting is another effect caused by the dense atmosphere, which rotates east to west around Venus (see Chapter 13).

As their size increases, infalling objects reach a point where they punch through the atmosphere and strike the surface. However, craters less than about 30 km in diameter are usually irregular or multiple excavations (*Figure 3*). An irregular outline and hummocky floors tell us that a meteoroid probably broke apart during passage through the dense Venusian atmosphere. After breaking up, the meteoroid fragments struck nearly simultaneously, creating the crater cluster.

Most of the nearly 1,000 craters scattered over the surface of Venus are gemlike works of art. Almost all appear to have formed recently — their rims are sharp, and the surrounding blankets of ejected debris look undisturbed. However, such appearances are deceiving, as Venus's craters have been accumulating over the past few hundred million years at an average rate of only one or two per million years. The excavations appear fresh because the processes of erosion on Venus are slow. Despite the dense atmosphere, wind speeds are too low to wear down the terrain, and as mentioned water is not a factor.

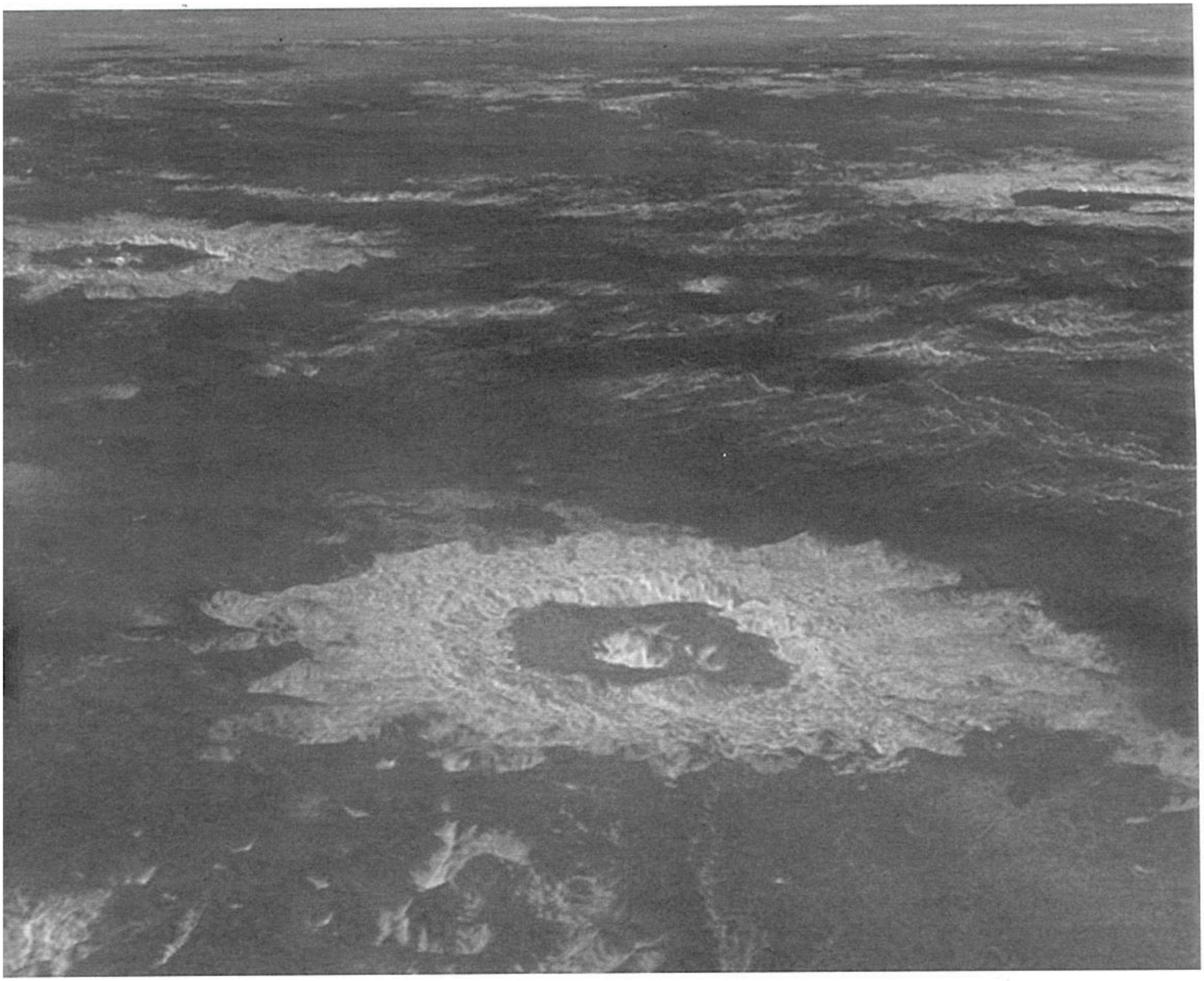
A good example of one of the more typical Venusian craters is Aurelia (*Figure 4*). Named for the mother of Julius Caesar, 32-km-wide Aurelia is a complex crater with a circular rim, terraced walls, and central peaks — all rather common features. The pattern of surrounding ejecta spreads out like a butterfly's wings, with relatively little in the direction from which the meteoroid descended. This asymmetry is seen frequently around craters on other planets, and it results from an oblique (not vertical) impact. The collision's energy melted a large amount of the target rock, which can be seen flowing out into the ejecta blanket. Much of this apron appears bright in the radar image, as does the crater floor, which implies that it is very rough.

Another crater with asymmetric ejecta and bright flows is Jeanne (*Figure 5*). It is surrounded by dark material of two types. On the southwest side is an area of smooth (radar-dark) lava flows that run out into the surrounding brighter flows like long fingers. The very dark area on the northeast side is probably covered by smooth material such as fine-grained sediment. This dark halo mimics the shape of the ejecta blanket. It may have been caused by an atmospheric shock or pressure wave produced by the incoming body. Jeanne also displays several distinct lobes to its northwest. These features may have formed by fine-grained ejecta transported by a hot, turbulent wind immediately after the impact. Alternatively, they may denote flows of impact melt.

The Magellan scientists were able to combine topography obtained by the radar system's altimeter with the images and reproject them in the computer to produce perspective views. The example seen in *Figure 6* includes the midsized impact craters Howe, Danilova, and Aglaonice, which are situated relatively near one another in a region south of the equator known as Lavinia Planitia. All three craters have floors covered with smooth, radar-dark lava. Oblique, three-dimensional portrayals like this one proved very useful in determining the often-complex geologic relationships present on the surface.

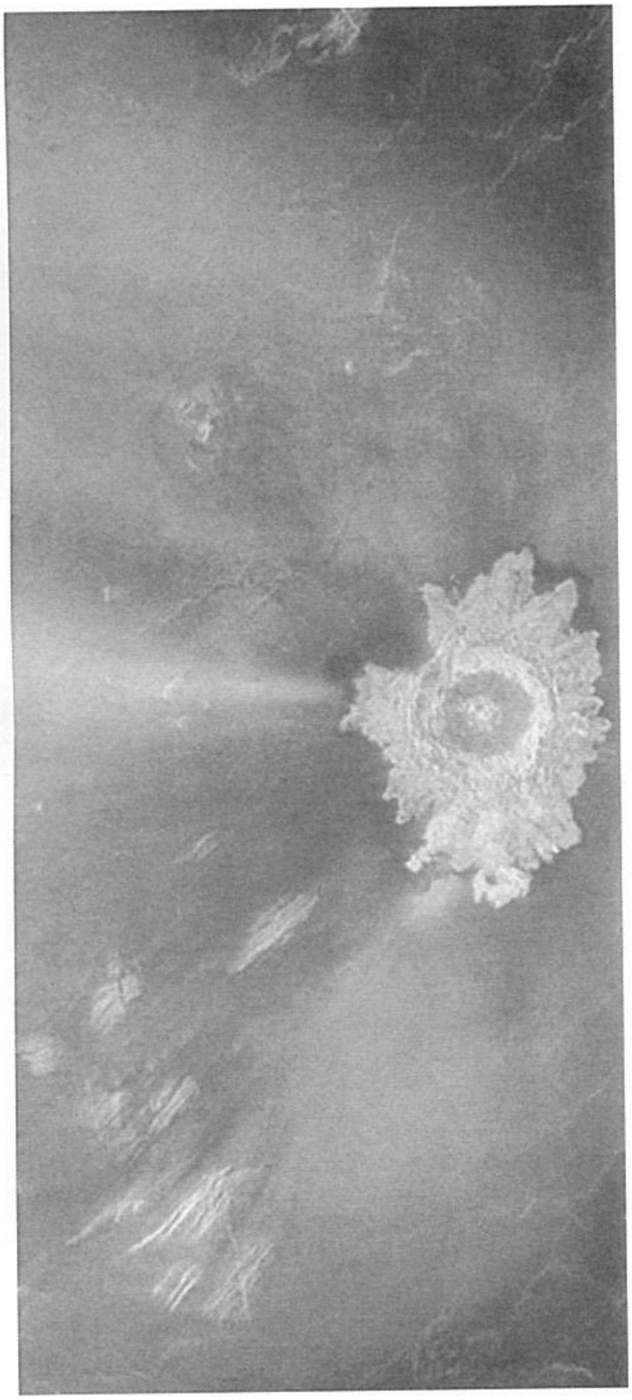
Many of the largest Venusian craters have another very interesting feature, which is illustrated by the crater Adivar (*Figure 7*). Some 50 km above the surface, the atmosphere of Venus maintains a strong, continuous flow, analogous to a jet stream, that blows more than 150 km per hour from east to west. When a large crater forms, its ejecta are thrown up into this flow and carried downwind. Surrounding Adivar's rim is ejected material that appears bright in the radar image due to the presence of rough fractured rock. However, a much broader area has also been affected by the impact, particularly to the west of the crater. Radar-bright materials, including a jetlike "tail" due west of the crater, extend for over 500 km across the surrounding plains. A darker apron surrounds the bright area in a horseshoe shape. These radar-dark (smooth) parabolic hoods surround many Venusian craters. However, bright streaks are rarer. Seen only on Venus, they result from the interaction of crater materials (the colliding meteoroid, ejected target rock, or both) and high-speed winds in the upper atmosphere. The precise mechanism that produces the streaks is poorly understood, but it is clear that the dense atmosphere of Venus plays an important role in the cratering process.

Figure 6. This simulated three-dimensional view is from a vantage point southwest of Howe, the 37-km-wide crater centered in the lower portion of the image. To its upper left is Danilova, with a diameter of 48 km, and at upper right is Aglaonice, 63 km across. The orangish hues are based on color images recorded by the Soviet Union's Venera 13 and 14 spacecraft, which viewed the surface as seen by sunlight filtered through the planet's dense clouds.



PLANETWIDE VOLCANISM

Volcanoes are among the most common geologic features in the solar system, and they are ubiquitous on Venus. Long before Magellan's arrival, evidence for a basaltic (volcanic) surface composition had been recorded by the seven Venera landers. Some of these spacecraft acquired images of the Venusian surface (*Figure 8*), which revealed flat-looking rock plates separated by small amounts of soil. The surface looks like some basalt flows in Hawaii and on the Snake River Plains of Idaho. The Veneras' chemical analyses determined that the rocks are indeed basaltic in composition. Basalts generally form from the melting of mantle materials, and they are abundant on each of the terrestrial planets and the Moon.



The global topographic mapping done by the Pioneer Venus orbiter and Magellan show that relatively flat plains cover about 85 percent of the surface of Venus. They tend to occupy the planet's lowest elevations (*Figure 9*). Magellan's radar images reveal that these plains are essentially all volcanic, though the source vents for all these flows are generally not apparent. However, the plains do contain meandering "rivers" that appear similar to lava channels on Earth and the Moon. These must have transported molten rock of some kind, since water is not presently stable on the Venusian surface. Although the channels generally lack tributaries, they often display levees, deltas, and abandoned bends. One particular channel, named Baltis Vallis, is 6,800 km in length — the longest sinuous rille yet identified in the solar system (*Figure 10*).

Approximately 1,100 volcanic constructs have been identified on Venus, which have been classified into groups according to the diameters of the bases. The most common edifices are small shield volcanoes with roughly circular outlines, diameters less than 20 km, commonly with summit pits (*Figure 11*). Such small shields are abundant on Venus. They are often found clustered together in shield fields that include identifiable lava flows. While the volcanic deposits associated with these shields are small in terms of volume, their sheer numbers and global distribution on Venus suggest that they may have contributed significantly to the formation of the crust.

Volcanic constructs of intermediate size, 20 to 100 km across, may have circular shapes like small shields or distinctive radial deposits emanating from a circular or elongated central vent. Flat-topped, steep-sided domes also occur in this size range (*Figure 12*). The shape of these latter domes implies that they formed from sluggish, viscous lava. They look similar to chemically differentiated lava domes on Earth. Although they are much larger, these domes are the best evidence for evolved (silicon-rich) magmas on Venus. Magma viscosity can also be increased if the melt is partly crystallized or contains abundant gas bubbles. The latter situation may result from the high atmospheric pressure at the Venusian surface (about 90 bars). In this high-pressure environment, gases that would ordinarily escape freely from the magma remain trapped within it, leading to explosive eruptions.

Some of the largest constructs on Venus, those at least 100 km in diameter, share many characteristics with large volcanoes on Earth. These often display lava flows emanating radially outward from a region of current or former high relief. Sapas Mons (*Figure 13*) is typical of the planet's large, shield-type volcanoes. Measuring 400 km across its base and 1.5 km high, Sapas has a collapse caldera at its summit. It's lava flows extend for hundreds of kilometers across the surrounding, fractured plains.

Coronae form a distinctive class of large volcanoes that were first identified on Venus in Venera radar images. Coronae are characterized by large, concentric rings of fractures, within which large volcanic outpourings have occurred repeatedly

Figure 7. **This 30-km-wide crater, named for the Turkish educator and author Halide Adivar (1883–1964), is located just north of the western Aphrodite highland at 9° north latitude, 76° east longitude. Its bright, streamlined hood and tail resulted from the interaction of ejected debris with high-altitude winds blowing from the east (right).**

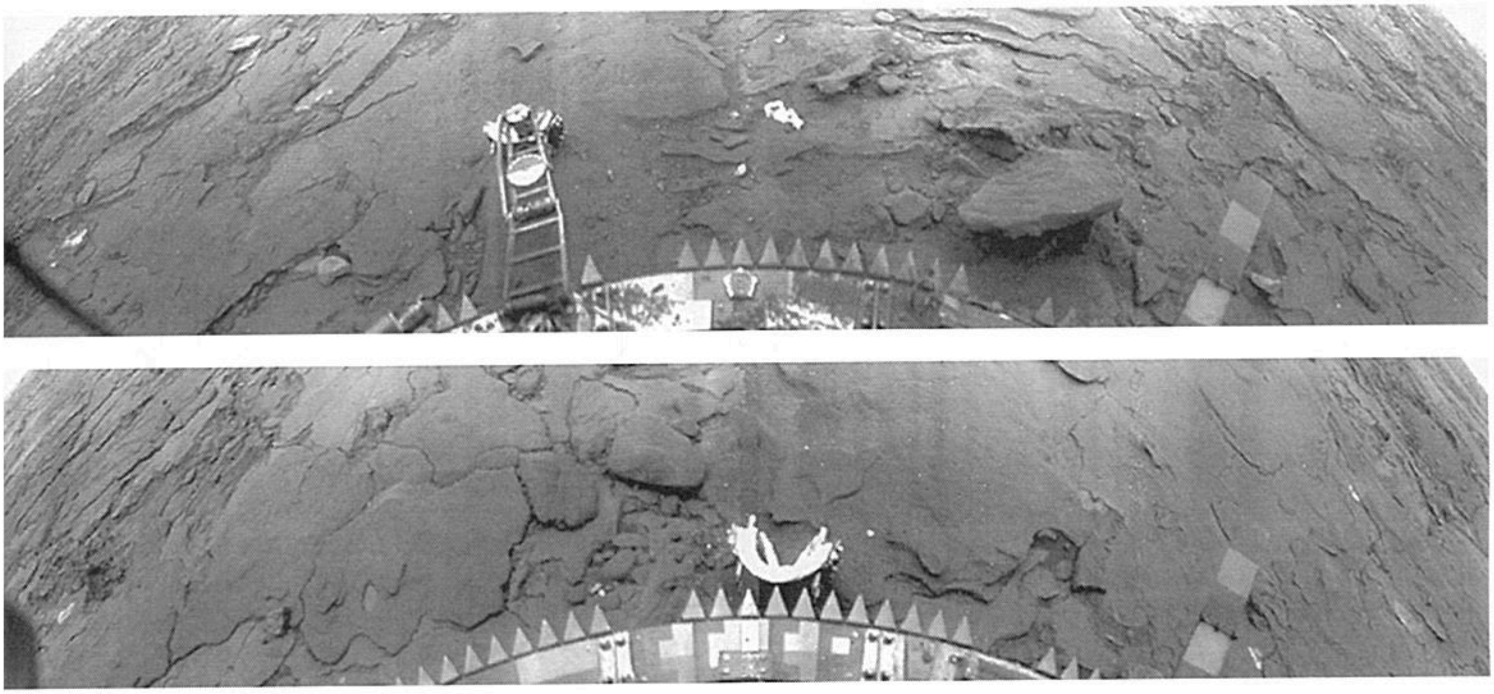


Figure 8. On 5 March 1982 the Venera 14 lander touched down on Venus at 13° south latitude and 310° east longitude, where it survived for 60 minutes before succumbing to the planet's heat. In that time it radioed to Earth these images of the Venusian surface, which include parts of the lander at bottom (a mechanical arm can be seen in the upper image, a lens cover in the lower one). The landscape appears distorted because Venera 14's wide-angle camera scanned in a tilted, sweeping arc. The horizon appears in the upper left and right corners of each scene, and the views are remarkably free of atmospheric haze. Note the dominance of slabby or platy rocks, separated by minor amounts of soil. The composition and texture of these rocks is similar to terrestrial basalts.

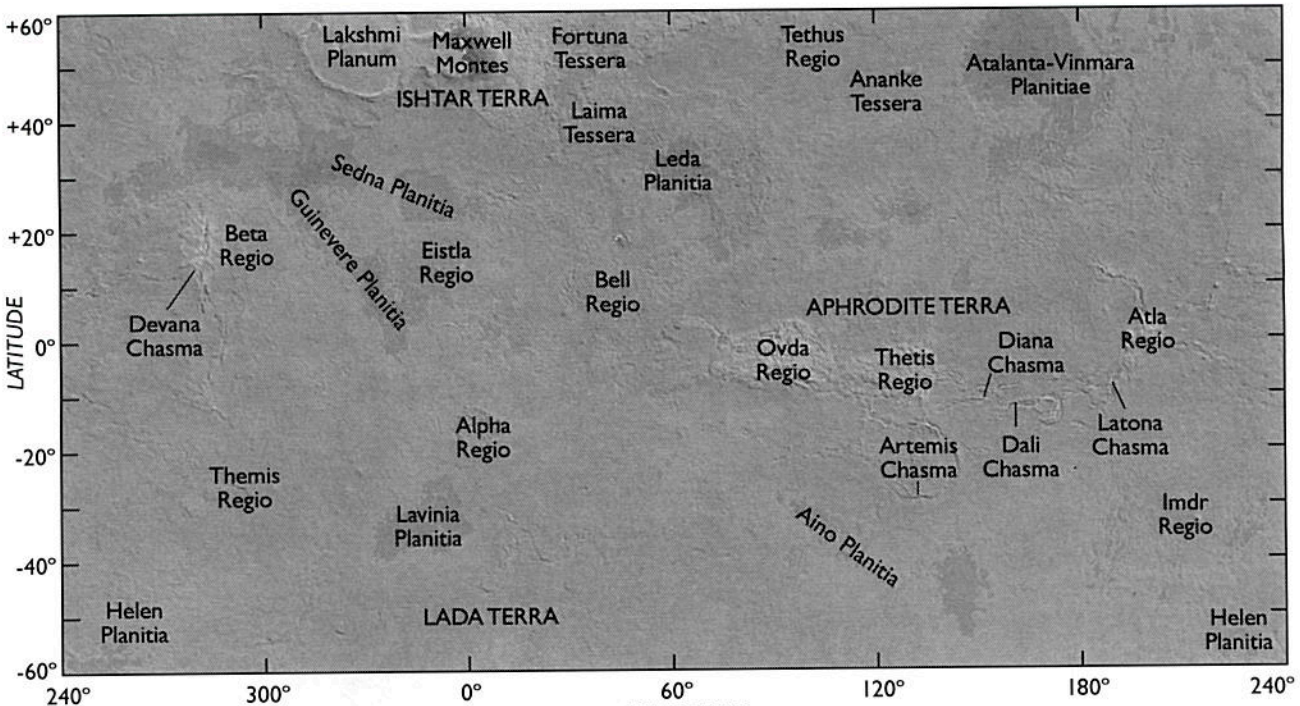


Figure 9. It took Magellan's radar altimeter 24 months to map 98 percent of Venus. In this Mercator-projected view, red corresponds to the highest elevations, blue to the lowest. Maxwell Montes, the planet's highest mountains, rise 12 km above the mean elevation. Even though Venus exhibits a range of elevations comparable to that of Earth, the two planets have distinct topographies. Earth has many high-standing continents and low-lying ocean floors, whereas about 60 percent of Venus's terrain lies within 500 m of the mean planetary radius (its equivilent of sea level). The scorpion-shaped feature extending along the equator between 70° and 210° east longitude is Aphrodite Terra, a continentlike highland that contains several spectacular volcanoes at its eastern end: Maat Mons, Ozza Mons, and Sapas Mons.

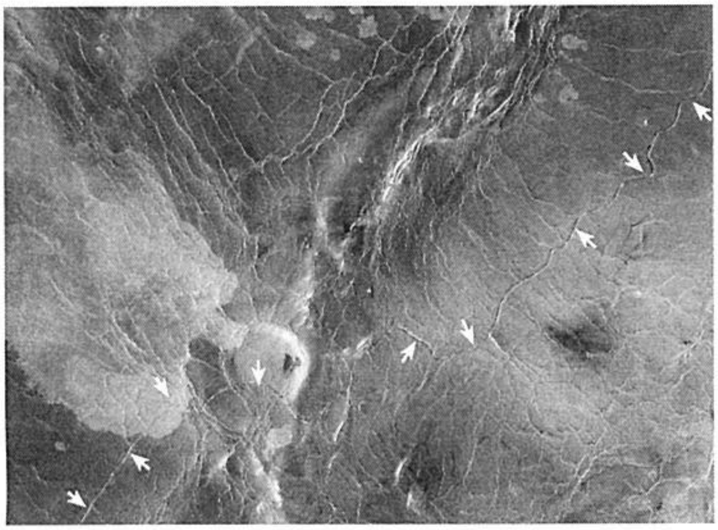


Figure 10. Baltis Vallis (indicated by arrows) snakes across the Venusian landscape for an amazing 6,800 km. Its great length and nearly constant width imply that it was fed by lava at a vigorous rate. The lava must also have been a very fluid material, such as komatite (a high-temperature basalt), carbonatite (an igneous rock made of calcium carbonate), or sulfur. Whatever the material, channels like this one record the last stages of widespread plains emplacement on Venus.

Figure 11 (right). Scores of small volcanic domes, all less than 15 km across, pepper the southern flank of a highland area known as Tethus Regio. Their shape is more reminiscent of Hawaiian-type shield volcanoes than of cinder cones. These pocklike edifices often appear in dense swarms and may total in the hundreds of thousands.

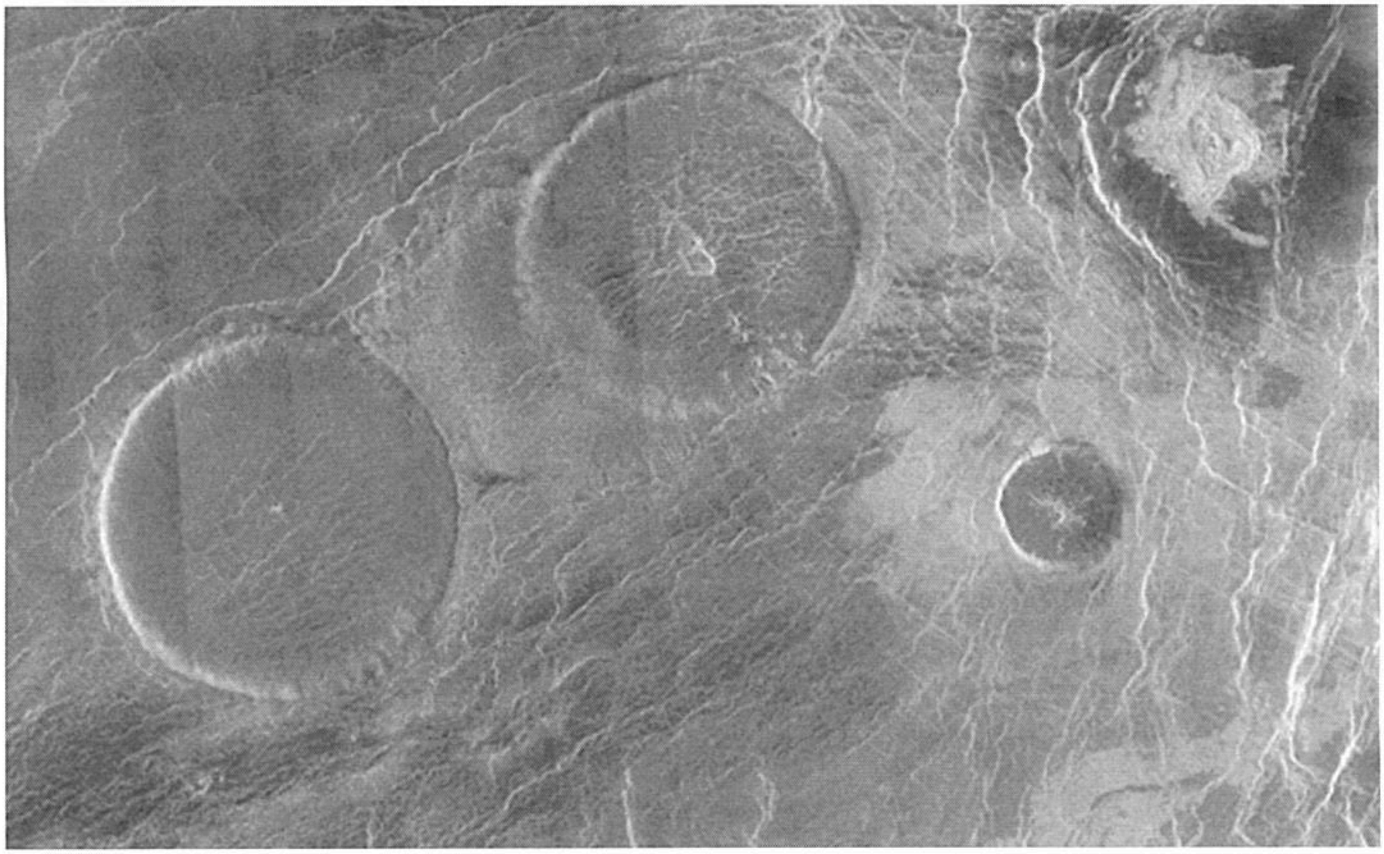


Figure 12. These "pancake" domes in the Eistla region of Venus are 65 km in diameter with broad, flat tops less than 1 km high. The cracks and pits commonly found in these features result from cooling and the withdrawal of lava. Note the more-fluid flow emitted from the dome above center that moved toward the other large dome at lower left. An irregularly shaped, radar-bright impact feature is at upper right.

(*Figure 14*). Such features are often surrounded by an annulus of ridges and troughs, which cut (in places) across fractures aligned more or less radially. The centers of the features also contain radial fractures as well as volcanic domes and flows. Coronae are thought to form due to the upwelling of hot material from within the mantle of Venus. The rising mantle plume causes the overlying crust to bulge and fracture, which leads to frequent episodes of volcanism. When the upwelling subsides, the bulge deflates, producing the fractured annulus.

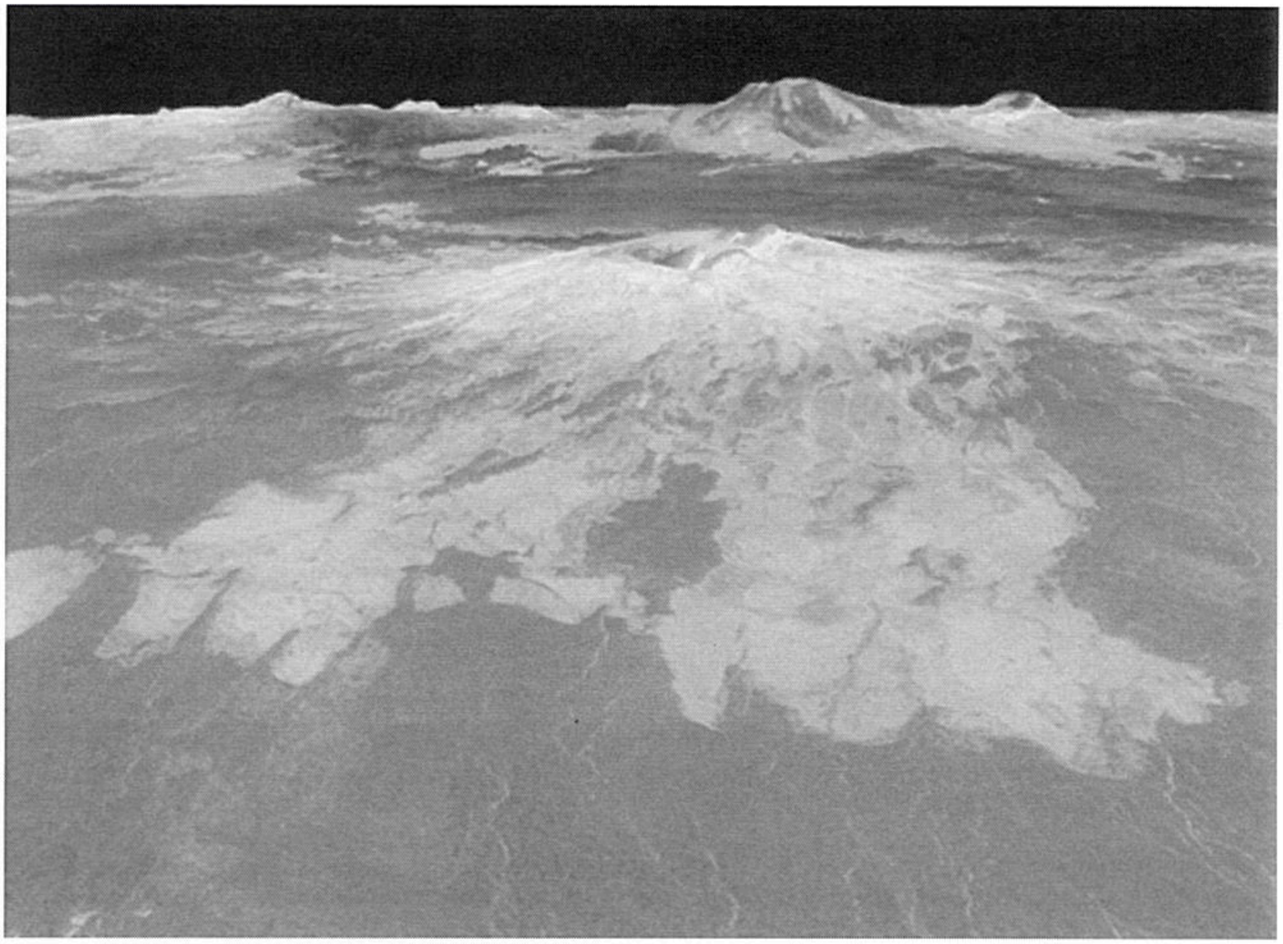
Both large volcanoes and coronae on Venus are preferentially associated with rift zones, volcanic rises, and chasms concentrated at the equatorial latitudes. Indeed, the spatial distribution of volcanic centers on Venus is concentrated in an area bounded by Atla, Beta, and Themis Regiones which are large topographic swells thousands of kilometers across. Beta, in particular, displays all the characteristics of a dynamic rift zone (*Figure 15*). These volcanic swells probably sit directly over localized mantle upwellings, and they may be actively erupting now. However, despite their association with rift zones, volcanic features on Venus are not concentrated along linear boundaries or in chains as on Earth. This is the primary evidence against a global system of crustal spreading and subduction on Venus. Instead, the planet probably has developed a different mechanism for crustal recycling (see Chapter 12).

Stratigraphic relationships clearly show that the large volcanoes have erupted onto the widespread plains in geologically recent times. This is borne out by the fact that there is a relative paucity of craters on large volcanoes compared to the global average. It is also true of the most recent coronae deposits. However, structures associated with corona formation are seen throughout the planet's stratigraphic record. From this we conclude that coronae have a long evolutionary history. The sequence of feature emplacement paints a picture of change over time. Initially the volcanoes spewed forth abundant lavas thick enough to bury preexisting craters and form sinuous channels. Then the activity became localized and concentrated at volcanic rises and individual edifices.

EXPRESSIONS OF TECTONISM

Fifteen percent of the Venus surface comprises highland plateaus and mountain belts. Many of the terrains typical of highlands are found within Aphrodite Terra, which straddles the equator from 45° to 210°. Western Aphrodite is composed of regions called Ovda and Thetis, which stand about 3 to 4 km above the planet's mean radius (6,052 km). Ovda and Thetis are dominated by highly deformed crust called *tessera* terrain. First identified in the Venera data, tessera terrain is characterized by a very rough surface, topography that is elevated relative to its surroundings, and a complex deformation history involving at least two sets of intersecting structures (*Figure 16*).

Figure 13. **Magellan scientists combined radar-reflectivity data with topographic altitudes to create this computer-generated perspective view of the large volcano Sapas Mons. Another volcano, Maat Mons, appears on the horizon.**



Tessera terrain occupies about 8 percent of the surface area of Venus and may occur as small (tens of kilometers across) "islands" within the plains. The tesserae are embayed by the volcanic flows that cover the widespread plains and thus are commonly the oldest preserved unit in any given area. This observation is supported by the work of Mikhail Ivanov and Alexander Basilevsky, who found that crater counts on tesserae are up to 40 percent higher per unit area than the global average. However, the tesserae are not ancient highlands like those on the Moon. Instead, they record complex deformation that occurred just prior to the eruption of the global plains.

Ridges, fractures, and graben are ubiquitous within tesserae and are accompanied by minor amounts of volcanism. Large tessera plateaus, such as Ovda and Thetis, typically have relatively steep-sided margins that stand higher than the plateaus' interiors (*Figure 16*). At the time of this writing, the sequence of tessera evolution is under debate. Do the extensional structures we find there predate those involving contraction, or vice versa? This sequence is critical to understanding whether the plateaus formed as regions of crustal thickening due to magmatism or due to horizontal compression. The local gravity signature of large tessera plateaus shows them to be *isostatically compensated* at present. This means they are floating in equilibrium atop the mantle, like icebergs, and not supported from below by deeper upwellings. Just the opposite is true for prominent volcanic rises like Atla Regio and Beta Regio, which have attained significant elevation largely because they are being pushed upward and supported from below by hot, rising mantle plumes.

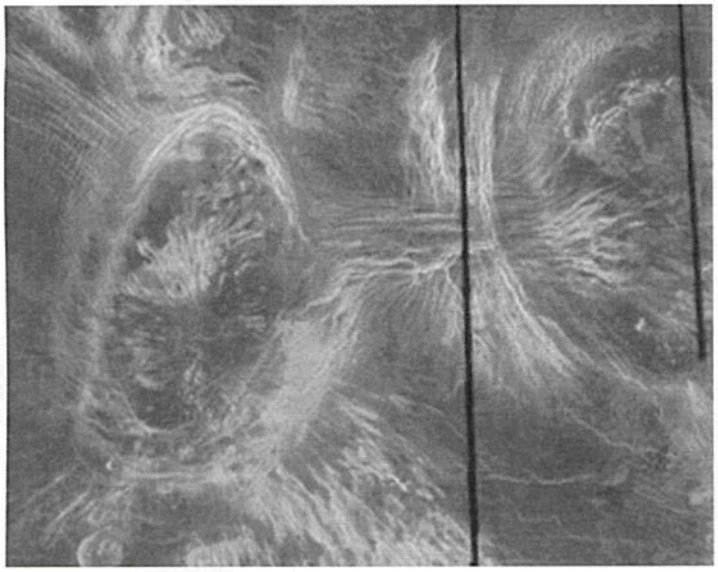


Figure 14. **This mosaic of Magellan data in Fortuna Regio contains two large coronae: Bahet (at left, 230 km across) and Onatah (350 km across).**

The eastern portions of Aphrodite are cut by a series of a deep, narrow canyons that extend eastward toward Atla Regio, where they are joined by large volcanoes such as Maat Mons and Sapas Mons. As they cross Atla and Beta, these *chasmata* consist of abundant faults and graben, which form rift zones with up to 6 km of vertical relief (*Figure 17*). The shape and scale of these zones are similar to those of terrestrial rifts such as the East African Rift. Despite this resemblance, in the Venusian situation volcanism is confined to individual edifices along the rifts and does not directly emanate from the rift itself, as occurs at mid-ocean ridges on Earth. This argues against these rifts being sites of plate spreading.

Perhaps the most recognizable tectonic feature on Venus is a high-standing "continent" at far northern latitudes called Ishtar Terra. Mountain belts feature prominently within western Ishtar (*Figure 18*), while the eastern half consists largely of Fortuna Tessera. In between is an impressive mountain chain called Maxwell Montes. (Named after famed physicist James Clerk Maxwell, it is the only Venusian feature that honors a man; all the rest recall important women in history or mythology.) Maxwell forms the eastern boundary of an elevated plateau, Lakshmi Planum, which is bounded on its north, west, and south by the mountain belts Danu, Akna, and Freya Montes, respectively. Lakshmi sits 4 km above the planet's mean radius and is dominated by volcanic plains and two major shield volcanoes.

The steep slopes (up to 35°) and unique elevation (12 km) of the Maxwell Montes mean that something unusual is taking place underneath. Either this chain formed relatively recently in Venusian history, or the strength of the underlying crust is quite high, or the mountains consist of low-density rock. Although most investigators agree that Ishtar was somehow created under compression, the mechanisms of formation of this enigmatic structure remain equivocal (see Chapter 12).

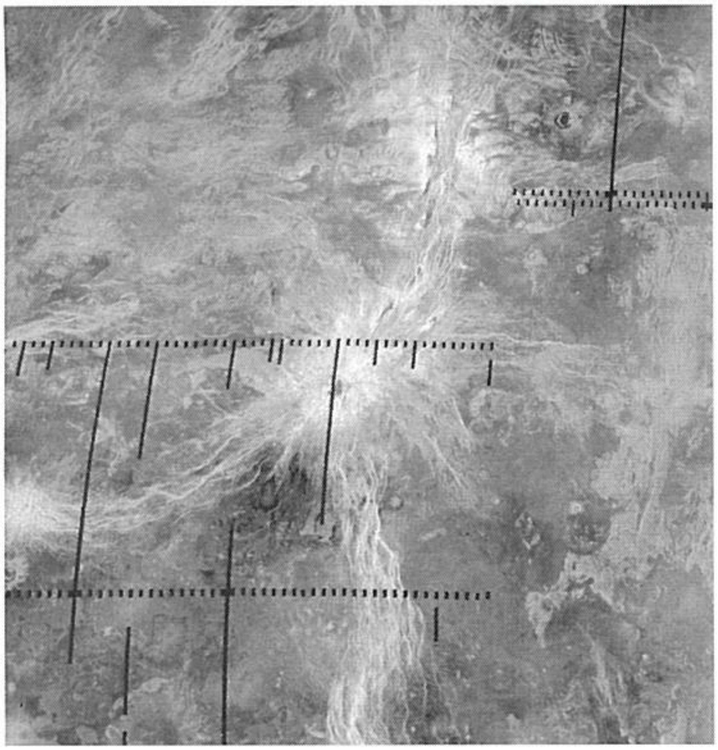


Figure 15. **The dramatic complex known as Beta Regio is considered one of the youngest and most dynamic features on Venus. Its two radar-bright peaks, Rhea Mons (top) and Theia Mons, are sliced open by a huge north-south rift known as Devana Chasma. Many faults radiate outward from the two tectonic centers, about 1,100 km apart The rough surface of Beta Regio makes it very reflective at radio wavelengths, and it was among the first features seen on Venus in the 1960s during the infancy of ground-based radar experimentation.**

Figure 16. **The northern boundary of Ovda Regio, one of the large highlands ringing the equator of Venus. Arcing ridges mark a boundary where the elevation drops 3 km from Ovda to the surrounding plains. Some of the ridges have been cut at right angles by extension fractures. Dark material, interpreted to be lava, fills the region between the ridges. The curvilinear, banded nature of these ridges suggests that compression contributed to their formation. The image is about 300 km across.**

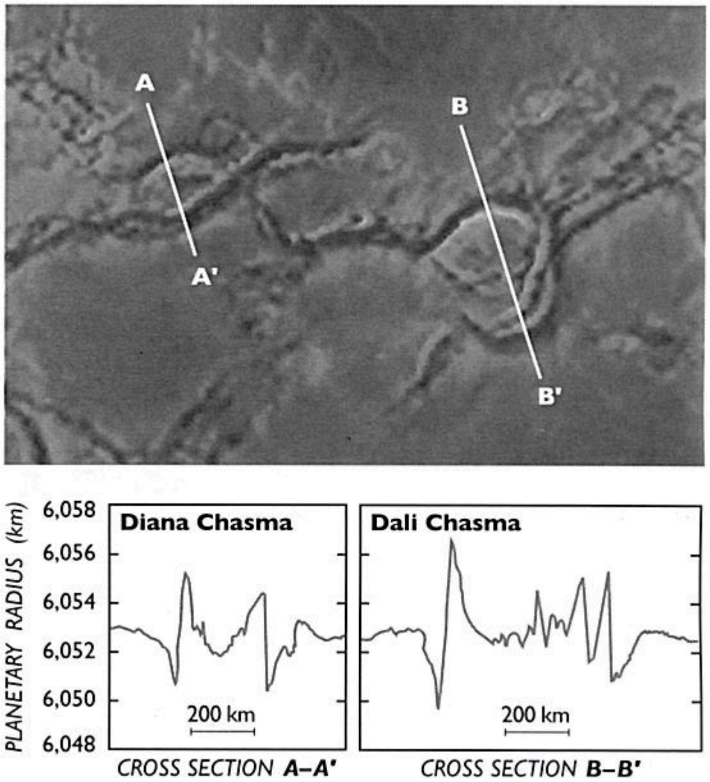


Figure 17. **Diana Chasma and Dali Chasma are two major canyons near the ea end of Aphrodite Terra. Each has a raised rim on one side that abruptly drops several kilometers to the floor below (heights in the graphs are exaggerated b factor of 100).**

One of Magellan's discoveries is that tectonic features are rather ubiquitous throughout the volcanic plains. Unlike the situation on Earth, where such features tend to be concentrated in localized areas, on Venus they are distributed across large regions. Wrinkle ridges are the most common feature on the plains. These long (10 to 50 km), narrow (about 1 km), sinuous features often occur in evenly spaced, parallel sets. Most likely they form under compressive stress. Wrinkle ridges are superimposed upon, and thus postdate, the widespread regional plains. However, they are not seen on the lobate flows associated with large volcanoes. Thus wrinkle ridges must be associated with the planetwide plains-forming event. Perhaps they reflect the stress fields that accompanied the formation of topographic features in many discrete, local situations. Interestingly, however, a global map of wrinkle-ridge orientations shows them to align circumferentially to the Aphrodite Terra highland. This suggests that the ridges may have been influenced by the stress field associated with the highland.

The plains also include regions of more concentrated tectonic deformation, termed *ridge belts,* which were identified in the planet's northern hemisphere in the Venera 15 and 16 data. The belts typically rise a few hundred meters above the surrounding plains, and they can be tens of kilometers wide and hundreds long. They may consist of a single broad arch or a complex assemblage of smaller ridges. Ridge belts are concentrated within or near the major lowlands, including Atalanta Planitia and Lavinia Planitia. In Lavinia, the ridge belts are joined by fracture belts of similar dimensions, though oriented orthogonally to the ridges (*Figure 19*).

Lavinia's ridge belts are examples of localized deformation in the broad, lowland plains. The ridge-fracture systems there and elsewhere on Venus are embayed by lava flows that themselves bear wrinkle ridges typical of distribution plains deformation. This suggests that both features may have formed under a similar stress field. Additional evidence for broad crustal deformation comes from 6,800-km-long Baltis Vallis, which shows variations in elevation along its length of up to 2 km. Assuming that Baltis formed on an initially flat or gently sloping surface, these topographic variations reflect vertical movements of the crust that have occurred since the plains were emplaced. The tilting of plains at tessera boundaries also reflects broad scale topographic adjustments of the crust.

All these stratigraphic relations give us details on the sequence in which Venus's features came to be. The tessera and lineated plains are the oldest units, and they indicate early episodes of faulting, folding, and perhaps mountain building. These units are typically embayed by the volcanic plains. Due to the absence of identifiable individual lava flows, we suspect that the plains resulted from widespread lava flooding. Plains emplaced more recently include bright, digitate, dark, and mottled plains, all of which are linked to volcanism in some form (individual vents, fractures, and coronae). Other features associated with recent volcanism are large individual edifices like Sapas Mons and the clusters of shields and domes. In a number of areas, ridge belts and fracture belts deform older plains, and these must therefore correspond to some of the most recent tectonic activity that has occurred on Venus.

The distribution of these geologic units is not uniform. The region bound by Atla, Themis, and Beta is dominated by fracture belts (corona chains), mottled plains, and volcanic edifices.

Tessera terrains are relatively rare in this area. In comparison, the area bound by Ishtar Terra to the north and Aphrodite to the south contains large concentrations of tesserae and regional plains, with few large volcanic edifices present. Many ridge belts are clustered in the north polar region between longitudes 180° to 240°, and a second major ridge-belt province is located near the south pole in Helen Planitia and Lavinia Planitia. In addition, this part of the planet contains the greatest concentration of large, visually distinct lava flow fields. We suspect that this southern region, along with the features Beta, Atla, and Themis, contains some of the planet's most recent lava deposits. Also probably quite young are the chains of coronae found along fracture belts in these regions.

REMINDERS OF EARTH

Venus has extremely slow rates of erosion compared to the spectacular effects caused by water and wind on Earth or even Mars. The atmosphere of Venus, though dense and moving quickly at higher altitudes, is actually rather sluggish right at the surface. There typical wind speeds are about as fast as a human walks. Although this is fast enough to move sand and dust, the slow speed makes the particles ineffective as cutting tools and agents of erosion. In Magellan's images, we see wind-related streaks in the lee of obstacles (*Figures 20,21*). These are not deposits of dust; instead, the wind has changed the surface in ways that make it rougher (and thus bright in the radar images)

Figure 18. **Western Ishtar Terra includes pear-shaped Lakshmi Planum, a volcanic plateau surrounded by mountain belts, and the radar-bright Maxwell Montes at right. Maxwell is the highest mountain chain on Venus, rising almost 12 km above the planet's mean radius. Its western (left) slopes are very steep, whereas the eastern slopes descend gradually into Fortuna Tessera. Broad ridges and valleys that make up much of Ishtar and Fortuna resulted from lateral compression within the crust. Most of Maxwell Montes reflects radar strongly, a common trait on Venus at high altitudes. This phenomenon is thought to result not from a rough surface but from the presence of an unusual radar-reflective mineral similar to pyrite. The prominent circular feature in eastern Maxwell is Cleopatra, a double-ring impact basin about 100 km across. Black wedges and rectangles indicate areas where the Magellan orbiter acquired no data.**

or smoother (darker). In *Figure 20*, notice how the wind changes direction from a southeast-northwest flow at the right of the image to an east-west flow at the eastern edge of the outflow channel. It is possible that many of the wind features on Venus were formed during short-lived "storms" created in the atmosphere by impact events.

Another type of surface process is landslides. Although not very common on Venus, landslides have produced some spectacular features (*Figure 22*). Some of these exhibit characteristics typical of terrestrial slumped blocks (masses of rock that slide and rotate down a slope instead of breaking apart and tumbling). In some cases the heavily scalloped hillside suggests that much more material has slid away than we see at the foot of the slope. Possible explanations for the missing debris are that it may have been covered by lava flows, the debris may have weathered, or that the radar may not be recognizing it because the individual blocks are too small.

These landslides and dust streaks — like the volcanism, faulting, and tectonism discussed earlier — are familiar features on planetary surfaces. In fact, except for the lack of water, most of the geologic processes that occur on Earth can also be seen in one form or another on Venus. The absence of water is actually a boon for planetary geologists. Because so little erosion has taken place, we have been able to study craters, volcanoes, tectonic features (faults), and the effects of wind and landslides in their pristine, original state.

Nonetheless, there are some profound differences between Earth and Venus. Most obvious (so far) is that each loses its heat in a different way. On Earth the crust is recycled laterally, through plate growth, motion, and subduction. By contrast, the volcanic and tectonic structures we've seen on Venus suggest that the recycling occurs vertically, with mantle upwellings triggering volcanism and mantle downwellings resulting in compression. One theory about why Venus does not exhibit lateral plate movement is its lack of water. On Earth, water is important in the formation of chemically differentiated magmas that comprise continental crust, and these in turn help maintain the cycle of subduction.

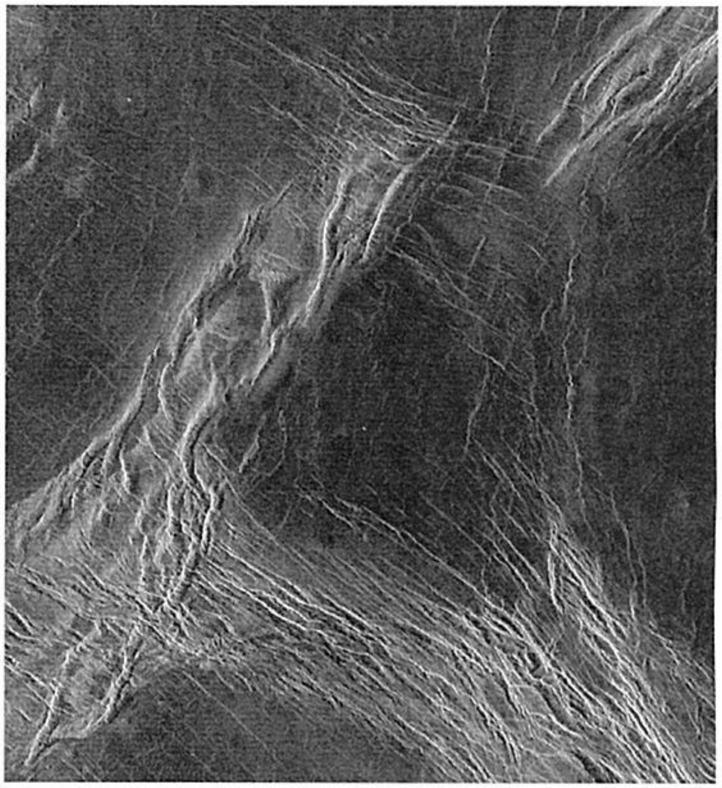


Figure 19. **This 400-km-wide mosaic of Magellan images is centered in Lavinia Planitia at 38° south latitude and 348° east longitude. A broad belt of tectonically formed ridges runs from upper right to lower left. Radar-dark areas between the ridges are relatively smooth and probably filled with lava flows. Note the set of thinner fractures running from upper left to lower right. This intersection pattern is seen throughout much of Lavinia and suggests that compressional and extensional forces have affected a very large region.**

Figure 20. **This section of Navka Planitia covers 180 km in width and 78 km in height. The two radar-bright deposits at center outline a channel that flowed from a 60-km-wide crater outside the frame to the south. Within the channel, outlined by "bathtub ring" deposits, are small cones most likely of volcanic origin. At the end of the outflow channel are bright features that may be sand dunes.**

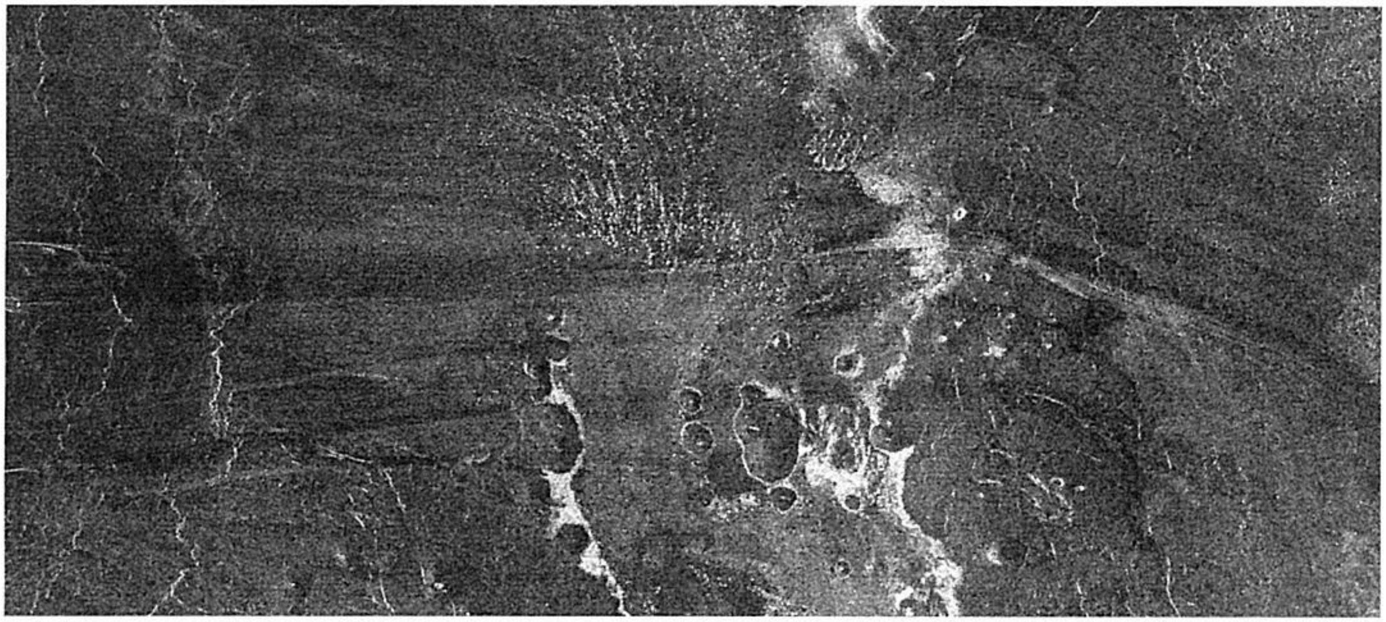


Figure 21. **A cometlike tail extends for 35 km from a small, isolated volcanic structure. Although only 5 km across, the volcano has slowed the region's northeast-trending winds enough to cause deposition of this radar-bright material. This scene is located at the western end of Parga Chasma at 9.4° south latitude and 247.5° east longitude.**

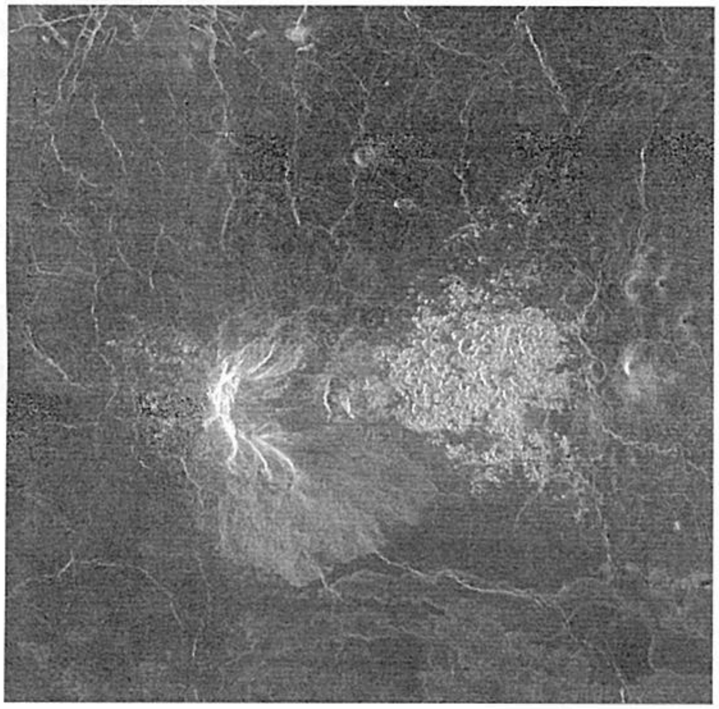


Figure 22. **The bright feature seen slightly south of center is a volcano, 15 to 20 km in diameter, with a large apron of blocky debris to its right and some smaller aprons to its left. Several large landslides dropped down steep slopes and were carried by their momentum out into the smooth, radar-dark lava plains. At the base of the east-facing or largest scallop on the volcano is what appears to be a large block of rock, 8 to 10 km in length. This image is about 120 km wide.**

What is amazing about Venus is that volcanic and tectonic resurfacing is not an ongoing process. Instead, it seems to have run rampant over a short period of time, obscuring all traces of what had occurred during the first 90 percent or so of the planet's history. This obliteration has robbed us of the opportunity to learn how and when the evolutionary paths of Venus and Earth diverged. The geologic rule of uniformitarianism — "the present is key to the past" — does not apply to Venus in the long-term sense. And so we wonder whether the ubiquitous volcanism seen on Venus today mimics the very early Earth or perhaps predicts an Earth yet to be. Will our planet's dynamic tectonism grind to a halt once its water disappears? Such speculations remain unanswered. For now, we are satisfied in having finally lifted the cloudy veil that has kept Venus's surface hidden for so long.

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