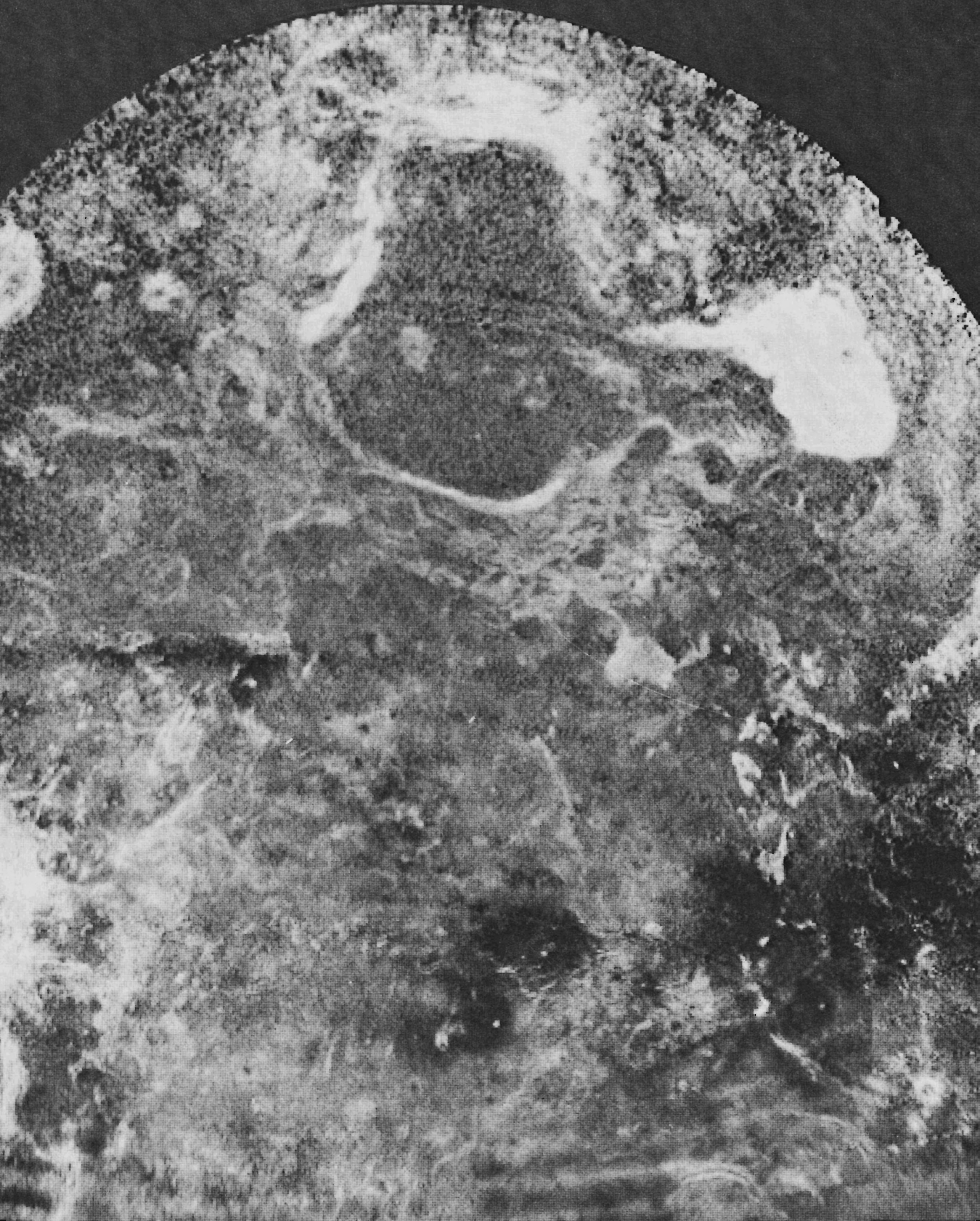

4
VENUS

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INTRODUCTION

Venus is of special interest to the geologist for the contrast it presents with Earth and for the clues it provides concerning Earth's origin and evolution. Both bodies are of similar size, composition, and distance from the Sun yet they have evolved to remarkably different states; one developed into a prolific haven for life, the other into a sterile inferno. Unfortunately, we are far from understanding why this happened. Geologic study of Venus is particularly difficult. The main obstacle is its thick atmosphere which prevents us from seeing the surface with either optical telescopes or conventional spacecraft imaging systems. Only in recent years, with the development of radar imaging techniques and deployment of landers on the surface, have we been able to get a glimmer of Venus' surface, and to begin its geologic study.

Venus is the brightest object in the heavens, after the Sun and the Moon. Because it lies inside Earth's orbit, its angular distance from the Sun is always small ($<47°$), so it is visible only at dawn and dusk. In ancient Egypt, Venus was seen as two objects—the evening star and the morning star. To the Phoenicians, Venus was Astarte; to the Chaldeans (Babylonians) it was Ishtar. The Chinese called it Tai-pe, which means Beautiful White One. The most ancient observations known were recorded by the Babylonians on the Venus Tablets around 1900 B.C. The correct reference to Venus is a matter of some debate. Moore (1961) used *Cytherean* as the adjectival form, a word derived from the old Sicilian name for Venus. As that term is probably unfamiliar to most, the more straightforward *Venusian* is used here.

Observations of Venus played a key role in testing the Copernican theory of the solar system against the hypothesis that Earth lies at the center. The test proposed by Copernicus was to observe the phases on Venus and thus demonstrate that it revolves around the Sun. Galileo observed the phases and revealed his discovery in a message to Kepler, which Galileo coded to allow more time to confirm the discovery and to establish his priority. The message to Kepler was "Haec immatura, a me, iam frustra, leguntur—o. y.," which translates to "These things not ripe are read by me.", ignoring the two letters "o. y." that do not fit into the anagram. The message can be rearranged to read "Cynthia figuras aemulatur Mater Amorum," the real message, or "The Mother of Love emulates the phases of Cynthia."

EARLY TELESCOPIC OBSERVATIONS

Astronomers have been observing Venus through the telescope since the instrument was invented in the early part of the seventeenth century. Among the best known of the early observers is Christiaan Huygens, who reported that Venus is featureless. However, many subsequent observers noted markings of various kinds, including bright patches and polar caps, although the best observers reported none that were reliably repeated. The watchers of the bright spots attempted to determine the length of the Venusian day, and a surprising number deduced rotation periods nearly the same as those of Earth and Mars. These included Giovanni Cassini (23 hr 21 min), J. J. Cassini (23 hr 28 min), Schroter (23 hr 21 min), and Trouvelot (24 hr).

The most extreme estimate of the Venusian day was by Schiaparelli, the discoverer of the Martian canals, who suggested in 1891 that Venus has a rotational period equal to its orbital period of 224 days 16 hr

48 min. A short time later Lowell built his observatory in Flagstaff, Arizona, primarily to study Schiaparelli's Martian canals. Lowell also saw canals on Venus and in 1897 published a map of them. Although Lowell's Venusian canals were never confirmed by others using large telescopes, Lowell appears to have been convinced that the markings were real and further, that the 225 day period was correct. Moore (1961) argued, in discussing Lowell's beliefs, that Schiaparelli's estimate of close to 225 days could not be correct since thermal observations of the dark side of Venus gave no indication that the dark side is colder than the sunlit side. In the early 1960s several astronomers documented retrograde atmospheric motions of 100 m/s at the equator, which gives a four day cloud circulation period (Young and Young, 1975), but still gave no indication as to the rotation rate.

The first published speculation that Venus has an atmosphere appears to have been by Schroter in 1796. The first conclusive indication of its thickness was through spectroscopic work in the 1930s, which revealed at least 300 times as much CO_2 as in Earth's atmosphere. In the early literature, the high albedo of the planet was variously attributed to a variety of causes including dust clouds, formaldehyde, or salts such as NaCl or MgCl from dried oceans.

Another frequently cited phenomenon was the Ashen Light. Apparently first described by Father Johannes Riccoli in 1643 (Moore, 1961), the Ashen Light is a faint phosphorescence of the night hemisphere, normally seen when Venus is a thin crescent. The light appears to vary in intensity and has been ascribed to extensive twilight or to electrical phenomena such as aurora or lightning activity.

Many of the early observers were concerned with predicting and accurately measuring the timing of transits—the passages of Venus across the Sun's disc. Transits of Venus are infrequent because of the relatively large inclination of its orbit (3.4°). Currently, they occur in pairs separated by eight years (1631, 1639; 1761, 1769; 1874, 1882; 2004, 2012). Kepler was the first to predict a transit, the one on December 7, 1631, which Gassendi unsuccessfully attempted to observe. Horrocks was successful, however, in predicting and observing the next transit in 1639.

By the mid-eighteenth century there was great interest in careful observation of the transits of Venus for the purpose of determining the astronomical unit, and the transits of 1761 and 1769 were widely observed for this purpose. The 1768 expedition of Captain James Cook, for example, was charged by the Royal Society with the responsibility of observing the transit of Venus from Tahiti. The observations were made on June 3, 1769.

The most poignant story among those of the early transit watchers is related by Moore (1961). The French astronomer Guillaume Legentil set out for Pondicherry, India, in 1760. Delayed by the Seven Years' War, he arrived too late for the 1761 transit and decided to wait eight years in India for the next one. Unfortunately, on the day of the transit, June 3, 1769, it was cloudy, and a presumably despondent Legentil departed India for home, but was shipwrecked twice en route. Eleven years after setting out for India, he reached Paris only to discover that he had been presumed dead and his property distributed to his heirs.

ORBITAL AND ROTATIONAL MOTIONS

Venus moves around the Sun in an orbital period of 224 days 16 hr 48 min, an eccentricity of 0.0068, and an inclination of 3° 24′. The eccentricity is less than any other planet, and the inclination is greater than that of any other planet's but Mercury and Pluto. There are about 584 days between inferior conjunctions, the times of closest approach of Venus and Earth. The exact time varies by about four days because of orbit eccentricities. At the time of closest approach, the Earth–Venus distance is 44 million km, and the Venus disc, although not visible, is 64″ across. At superior conjunction, when Venus and Earth are on opposite sides of the solar system, Venus has an angular diameter of 9.5″. As seen from Earth, the greatest angular distance of Venus from the Sun is at dichotomy when the angular separation is 47°. When seen in the evening, Venus is waning; in the morning it is waxing as it approaches superior conjunction. It is most brilliant at an angular distance of 40° from the Sun.

The semi-major axis of the orbit is 0.723 AU, so the planet receives about twice as much solar radiation as Earth. However, Venus has a high albedo (0.71), compared with Earth (0.39) and the Moon (0.07), because of its continuous cloud cover. As a consequence, despite its closer proximity to the Sun, Venus absorbs less radiation than Earth, giving it an effective radiation temperature of only 224 K as compared with Earth's 253 K.

The Venusian day has been only recently determined from radar observation. As noted above, early telescopic estimates ranged from 23 hours to 225 days, and this situation prevailed until the late 1950s. In the early 1960s, radar started to be used to observe Venus. W. B. Smith of the Massachusetts Institute of Technology looked for a Doppler shift in the radar echo as evidence of rotation. Although the period was not determined, there was an indication that the motion was retrograde. During the conjunction of 1962, several workers (Carpenter, 1964; Goldstein, 1964; Muhleman, 1964; Drake, 1964) confirmed that Venus' rotation was retrograde and estimated the period as close to 250 days. The estimate was later refined to 242.6 ± 0.9 days (Goldstein, 1965). The best current estimate is very close to 243 days, with the rotation axis inclined at 177°. Because of the similarity in the orbital and rotational periods, the sidereal day differs significantly from the solar day, which lasts 116.8 Earth-days. To an observer on the surface of Venus, the Sun would rise in the west, and daylight would persist for 58.4 Earth-days with a sky resembling that of a dark overcast day on Earth.

EARTH-BASED RADAR OBSERVATIONS OF THE SURFACE

Radar observations from Earth, besides providing us with a measure of the Venusian day, gave us our first information about the planet's surface. Radar studies of Venus have since been carried out in the U.S. mainly at three observatories: Arecibo in Puerto Rico, which has a 300 m diameter antenna using mostly 70 cm wavelength; Goldstone in the Mohave Desert of California, which has a 64 m antenna and operates primarily at 12.5 cm wavelength; and Haystack in Massachusetts, which has a 43 m antenna that is used at 3.8 cm wavelength. High resolution radar data can only be obtained around inferior conjunction, or about every 19 months. At inferior conjunction, the same hemisphere of Venus always faces the Earth.

The first Venus observations were ranging for ephemeris development. These range determinations had about one kilometer accuracy by the late 1960s. By 1970, images had been obtained by each of the three major observatories. These images had a resolution of about 50 km and showed only that Venus has fixed features and that the radar reflectivity varies from place to place. The technique used is to separate the echo into range bins representing circular regions on the planet equidistant from Earth. The range bins are subdivided by Doppler provided by the slow rotation of Venus. This still leaves a north-south ambiguity, in that each resolution element in the northern radar hemisphere has a counterpart with the same range and Doppler in the southern hemisphere. This ambiguity is now removed by an interferometry technique first developed by Rogers and Ingalls (1969, 1970) using the MIT Haystack telescope. The technique was subsequently used by Campbell et al. (1970) at Arecibo and by Goldstein and Rumsey (1970, 1972) at Goldstone. The theory behind the technique was described by Shapiro et al. (1972) and had been previously applied to the Moon (Zisk, 1972). The first images of Venus showed several circular features that resemble impact craters. Reflectivity and altimetry maps have since been made of small regions, showing numerous other surface features (Rumsey et al., 1974; Goldstein et al., 1976, 1978).

The highest resolution mode of the Goldstone images is about 10 km linear radar resolution and the images typically cover about 8° radius or regions of the planet about 1600 km in diameter (fig. 4.1). The theory and data processing operations of three station interferometry for obtaining the topography is described in Jurgens et al. (1980). The standard error of their altimetry is about 35 m near the sub-radar point increasing to about one kilometer at 6°. Recent Goldstone radar images (Jurgens et al., 1980) reveal small mountains 30–60 km in diameter, 1–2 km high, with mean slopes of 2.5° to 3.5°. A strong dependence of reflectivity on incidence angle is observed, suggesting that the surfaces are relatively smooth at the 12 cm-wavelength used.

The highest resolution images are those from Arecibo, which range in radar resolution down to 3 km (Campbell and Burns, 1980; Head and Campbell, 1982). These have substantially better resolution than the Pioneer Venus radar images, although obviously restricted to the hemisphere that faces Earth during opposition. Campbell and Burns used Arecibo images to construct a mosaic that covers about 25 percent of the planet's surface at a resolution of 10–20 km (fig. 4.2). The area covered stretches from 260° to 30°E between latitudes 70°N and 50°S.

The radar images show considerable surface detail reflecting mostly roughness variations. Freyja and Akna Montes, north of Lakshmi Planum, Maxwell Montes, and Theia and Rhea Montes are particularly prominent, implying rough surfaces at radar wavelengths. Two types of circular features are present: large, smooth, quasi-circular regions with diameters between 200 and 1300 km, and bright regions generally less than 300 km. Especially intriguing in the

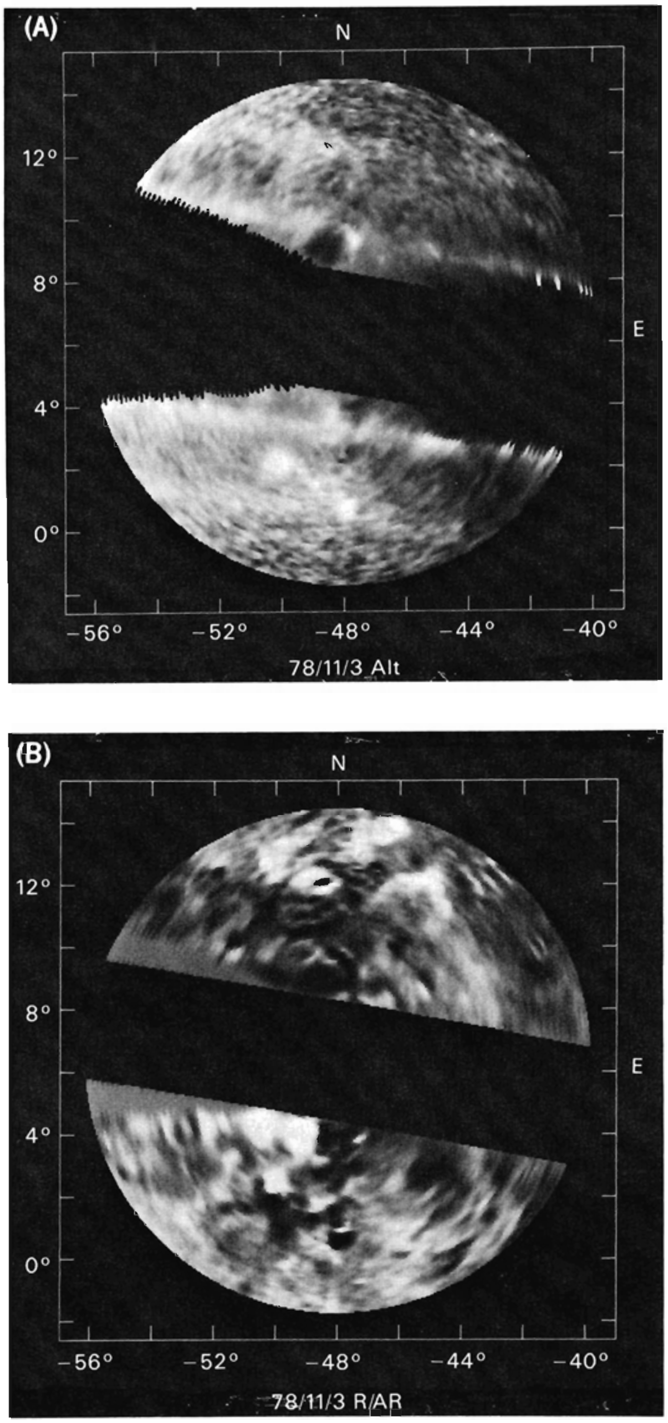

Figure 4.1. Goldstone radar images of a segment of the Venusian lowlands centered at 6°N, 312°E. (A) shows altimetry, the dark areas being low and the bright areas high. In the upper half is a crater 150 km in diameter and 750 m deep. Two bright spots in the lower half are isolated mountains, probably volcanoes. (B) shows variations in radar reflectivity for the same area. The variations are probably caused mainly by surface roughness, with bright areas rougher than dark areas.

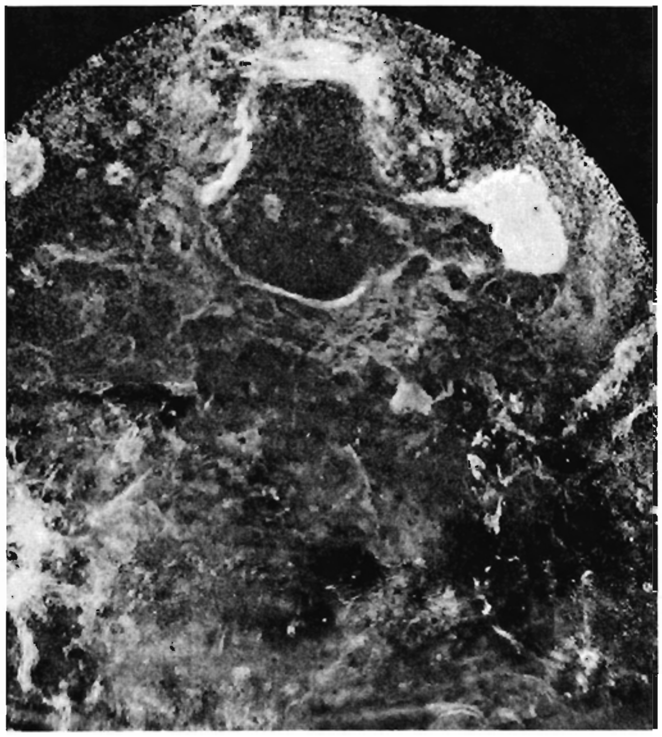

Figure 4.2. Mosaic of Arecibo radar images which covers about 40 percent of the northern hemisphere about the 330° longitude. The image shows variations in reflectivity of the surface at radar wavelengths. The prominent dark feature at the top center is Lakshmi Planitia with the very bright Maxwell Montes to the east. The bright marking at the lower left edge is Beta Regio. (Refer to fig. 4.6 to correlate with relief.)

highest resolution pictures are some banded terrain, suggestive of folded or faulted rock sequences (Head and Campbell, 1982).

SPACECRAFT OBSERVATIONS

The first U.S. spacecraft to observe Venus was Mariner-Venus 2, which flew by the planet on December 14, 1962 (table 4.1). It carried two primary experiments: a microwave radiometer to measure the surface temperature and the atmospheric structure and an infrared radiometer to determine the cloud structure and temperatures. The principal scientific results were the determination of a surface temperature of around 400 K and an indication that the magnetic field, or at least the dipole moment, must be less than 10 percent that of Earth. Mariner 2 also provided an order of magnitude improvement in the mass estimate for Venus (e.g., Anderson et al., 1964).

Table 4.1. Missions to Venus (from Colin, 1980)

Spacecraft	Launch	Encounter	Type	Encounter characteristics
Mariner 2	August 27, 1962	December 14, 1962	flyby	closest approach: 34 833 km
Venera 4	June 12, 1967	October 18, 1967	bus	burn-up
		entry probe	hard lander, nightside	
Mariner 5	June 14, 1967	October 19, 1967	flyby	closest approach: 4100 km
Venera 5	January 5, 1969	May 16, 1969	bus	burn-up
		entry probe	hard lander, nightside	
Venera 6	January 10, 1969	May 17, 1969	bus	burn-up
		entry probe	hard lander, nightside	
Venera 7	August 17, 1970	December 15, 1970	bus	burn-up
		entry probe	soft lander, nightside	
Venera 8	March 27, 1972	July 22, 1972	bus	burn-up
		entry probe	soft lander, dayside	
Mariner 10	November 3, 1973	February 5, 1974	flyby	closest approach: 5700 km
Venera 9	June 8, 1975	October 22, 1975	orbiter	periapsis: 1560 km; apoapsis:
		entry probe	soft lander, dayside	112 200 km; period: 48 hr, 18 m; inclination 34°10′
Venera 10	June 14, 1975	October 25, 1975	orbiter	periapsis: 1620 km; apoapsis:
		entry probe	soft lander, dayside	113 900 km; period: 49 hr, 23 m; inclination 29°30′
Pioneer Venus 1	May 20, 1978	December 4, 1978	orbiter	periapsis: <200 km; apoapsis: 66 000 km; period: 24 hr; inclination: 105°
Pioneer Venus 2	August 8, 1978	December 9, 1978	bus	burn-up, dayside
			entry probes	4 hard landers, dayside and nightside
Venera 11	September 9, 1978	December 25, 1978	flyby	closest approach: 25 000 km
		entry probe	soft lander, dayside	
Venera 12	September 14, 1978	December 21, 1978	flyby	closest approach: 25 000 km
		entry probe	soft lander, dayside	
Venera 13	October 30, 1981	March 1, 1982	entry probe	soft lander
Venera 14	November 4, 1981	March 5, 1982	entry probe	soft lander
Venera 15	June 2, 1983	October 10, 1983	orbiter	24 hr orbit, 1000 km periapsis
Venera 16	June 7, 1983	October 4, 1983	orbiter	24 hr orbit, 1000 km periapsis

Mariner 5, a spare Mariner-Mars 1964 spacecraft, was launched on June 14, 1967, and arrived at Venus on October 19, 1967. The main objective was to investigate the atmosphere, ionosphere, and magnetosphere of Venus; for the geosciences, an important result was an improved radius. Previous telescopic measurements had yielded a radius of 6120 ± 7 km (DeVaucouleurs, 1964). The radar determined radius was 6056 km (Ash et al., 1968). By combining the radio tracking of Mariner 5 with Earth-based radar reflections, a radius of 6054 ± 2 km was determined (Anderson et al., 1968). A high priority was to determine the atmospheric density and pressure at the surface. During an exciting five day period in October 1967, Mariner 5 arrived at Venus and the Soviet Venera 4 made a hard landing on the Venus surface. The Soviets put down a pressure sensor for a direct measurement of surface pressure, while the U.S. used radio occultations of the Mariner spacecraft. The surface temperature was about 700 K and the pressure about 100 bars. The cloud top was at 67 ± 10 km, and CO_2 was confirmed as the predominant atmospheric constituent. Measurements made by Venera 4 indicated that the magnetic field of Venus is <0.00001 that of Earth.

Over the next few years the Soviets sent several additional spacecraft to Venus and achieved the first soft landing on another planet when Venera 8 soft landed on the Venus surface on July 22, 1972. In addition to measuring various properties of the atmosphere during entry, the lander was able to measure the radioactivity of the surface materials with a gamma ray spectrometer (Vinogradov et al., 1973), and to obtain a measure of their density (1.5 g/cm^3).

The first spacecraft to orbit Venus were Veneras 9 and 10, placed in orbit in October 1975. They were in elliptical orbits with periapses of about 1500 km. The orbiters were not tracked continuously and were operated in a 3-axis stabilized mode only near periapsis. Elsewhere in the orbit they rotated slowly about the Venus–Earth direction. Veneras 9 and 10 also released landers to the surface and both successfully soft-landed. These landers carried an imaging system in addition to the gamma ray spectrometer/densitometer carried on Venera 8, and both spacecraft returned excellent pictures from the surface. In 1978 the Soviets sent two additional spacecraft, Veneras 11 and 12, to Venus, but neither returned useful data.

The U.S. also sent two spacecraft, Pioneer-Venus' 1 and 2, to Venus in 1978 (Colin, 1980). Pioneer 1 was an orbiter carrying a wide array of scientific instruments to examine the atmosphere, the surface, and the interaction of the planet with the solar wind. Of main geologic interest was a radar mapper designed to systematically map the elevation of the surface and its roughness. Pioneer 2 consisted of five separate spacecraft—a bus, a large atmospheric probe, and three small probes. The probes entered the atmosphere of Venus at different locations, two on the night side and two on the day side. Each carried several instruments designed primarily to determine the composition and structure of the atmosphere.

In 1981 the Soviets launched two more spacecraft to Venus, Veneras 13 and 14. In March 1982, both successfully soft-landed on the surface and photographed their surroundings. Both spacecraft carried an X-ray fluorescence instrument, which provided the first chemical analyses of the Venusian surface.

The most recent Soviet Venus missions are Venera 15 and 16. Identical spacecraft were placed in polar orbits to image the northern hemisphere using a radar system. Other experiments included a radiometer to measure surface brightness temperature, and altimeter to map surface topography, and an infrared spectrometer to obtain data on atmospheric composition.

The image resolution of Venera 15/16 radar is about 1.5 km. This is about the same as the best currently available Earth-based resolution from Arecibo (Campbell et al., in press). In comparable terms, the NASA Venus Radar Mapper will have a resolution of 180 to 460 m depending on position in orbit from periapsis.

Preliminary releases of the Soviet images show craters and linear tectonic features.

CONSTRAINTS ON THE COMPOSITION OF VENUS

The terrestrial planets are characterized as much by their differences as by their similarities and each must have started out on its unique evolutionary path as a result of conditions that prevailed very early in their history. Before examining the Venusian surface in detail, and trying to reconstruct the geologic history from the surface record, we will briefly examine what might be deduced about the planet's early history from models of formation of the planets. General models for compositional and density trends in the solar system have been developed by Lewis (1972, 1974) and Cameron (1963, 1973). In these models solid dust condensed in equilibrium with gas of the solar nebula at temperatures and pressures that varied with heliocentric distance (see Introduction). The dust grains accreted to form larger objects and ultimately planets. The more volatile the elements, or compounds, the farther out they condensed.

Condensation within a solar nebula that is cooling outward and with time, satisfactorily explains the gross compositional trends in the solar system, but the rare gases appear to follow an inverse trend. Pioneer-Venus discovered a large excess of nonradiogenic rare gases in the Venusian atmosphere. Neon and the nonradiogenic argon isotopes ^{36}Ar and ^{38}Ar are one hundred times more abundant on Venus than on Earth. In contrast, the mixing ratios for nitrogen and carbon dioxide are remarkably similar for the two planets. The volatile rare gases decrease in abundance outward rather than increase as the simple model predicts. The cause must be connected with the origin of planetary atmospheres. Pollack and Black (1979) outlined the basic theories of origin.

(1) Condensation/capture. Planets acquired their atmospheres from the primordial nebula or solar wind. Either source must have had a composition different from today's Sun.

(2) Cometary impact. Volatile-rich objects entered the inner solar system from the more distant parts where they had condensed. The objects accreted onto the inner planets, providing them with atmospheres. This model does not, however, explain the observed rare gas gradients.
(3) Grain-accretion. Pollack and Black (1979) proposed a grain-accretion hypothesis in which the rare gases became adsorbed on grains which were later accreted by the planets. The solar nebula, they postulated, had a relatively uniform temperature gradient but a steep pressure gradient, decreasing outward. Adsorption of volatiles is pressure dependent so that the grains that accreted nearest the center where the pressures were highest would have more adsorbed volatiles. Most of the non-rare gas volatiles such as nitrogen and water were chemically bound within the grains, and so their abundances were not as sensitive to the pressure gradient as the rare gases. The rare gases were thus fractionated with respect to the other volatiles.

Wetherill (1981) alternatively proposed that the solar wind accretion model best accounts for the observed trends. During the early stages of development of the solar system, material condensed from the nebula gas to form particles which accumulated into larger bodies (planetesimals), which in turn accumulated to form the planets. Wetherill suggested that the excess inert gases were implanted by an enhanced solar wind bombardment during planetesimal growth, and that the decreasing outward rare gas trends were produced by a geometric shading effect, causing implantation to be less efficient with increasing distance from the Sun because of shielding by particles closer in. Each planet preferentially incorporated material that had condensed in its part of the solar system, so that the planets nearer the Sun incorporated relatively more rare gases.

The origin of a planet's atmosphere is strongly coupled to its outgassing history. In general, the atmosphere does not represent the composition of the total inventory of degassed volatiles because most gases react with the surface materials or are lost by exospheric processes. Only the rare gases, except for He, are conserved. The isotopic abundance of rare gases, therefore, provides the best clues concerning atmospheric history but even these do not provide a unique solution. The outgassing history of Venus remains obscure, and will remain so until we obtain much more compositional information about the surface and the interior.

Presently, the composition of the interior of Venus is constrained only by the bulk density and inferences drawn from compositional determination made by the Soviet landers. After making corrections for the effects of compression, the density of Venus appears to be about 2 percent less than if it were compositionally identical to Earth (Ringwood and Anderson, 1977). Ringwood and Anderson argued that even if the high surface temperatures had persisted since the formation of the planet, the thermal wave could have penetrated only about 500 km. Temperature deeper than 500 km would be about the same as on Earth so that the density differences cannot be explained simply on the basis of the high surface temperatures. This argument assumes that heat is lost mainly by conduction, but the conclusion would be the same if heat transport was mainly by convection since the temperature at which mantle materials flow should be similar on both planets. Removing the effect of thermal expansion due to the higher near-surface temperatures on Venus lowers the bulk density somewhat, but still leaves an uncompressed density 1.7 percent smaller than Earth's.

The Lewis (1972, 1974) equilibrium condensation model qualitatively explains why Venus has a lower uncompressed density than Earth. Earth incorporated more sulfur than Venus, so has a higher sulfur to silicate ratio. Since sulfur has a greater atomic weight than the mean atomic weight of the silicates, Venus is less dense. However, Ringwood and Anderson suggested that there are problems with the equilibrium condensation model because they calculated the decrease in density resulting from removing all the sulfur from Earth's core and still concluded that Venus remains less dense. On the other hand, support for equilibrium condensation is provided by a model of sulfur chemistry in the atmosphere-lithosphere system based on Pioneer-Venus (Lewis and Kriemendahl, 1980) which suggested that the Venus lithosphere must have a far lower FeO content than Earth's. This is expected from the equilibrium condensation model, which predicts that FeO would not condense at the Venus distance.

Goettel et al. (1981) showed that the density differences between Earth and Venus can be eliminated by assuming a different temperature structure and a deeper basalt to eclogite transition. In addition, the low FeO content expected for Venus would tend to result in a lower observed (uncorrected) density for

Venus, since the depth to phase transitions involving olivine to spinel and perovskite structures is increased with decreasing FeO/(FeO + MgO) (Phillips and Malin, 1982). A low FeO content could also result in higher interior temperatures because iron-poor olivines have higher melting temperatures, and probably a higher viscosity at a given temperature, than iron-rich olivines. Temperature profiles may therefore stabilize at higher values in the iron-poor Venus mantle as compared with the iron-rich Earth mantle.

VENERA LANDER RESULTS

The Venera spacecraft have provided close-up views at four locations. Venera 9 landed on a rocky, sloping surface at 32°N, 291°E, on the eastern flanks of Beta Regio. The rocks are mostly flat and slab-like, ranging in size up to 70 cm in diameter and 20 cm high (Florensky et al., 1977). Many have fractures and grooves suggestive of layering. Between the rocks is a seemingly fine-grained, low-albedo material. Florensky et al. suggested that the slabs were in the process of slowly moving downslope by mass wasting. Three days later, on October 25, 1975, a second spacecraft was set down at 16°N, 291°E on a flat plain to the south of Beta Regio. The plain appears to be composed of scattered flat outcrops with darker, fine-grained material between. The outcrops are typically 1 to 3 m across and constitute about half the surface. The fine-grained material at this site also had a very low albedo (<3 percent); that of the rocks was close to 5 percent. After both landings, gamma-ray detectors were deployed to determine the radioactivity and density of the surface materials. At the Venera 10 site the material on which the detector rested has an estimated density of 2.8 ± 1 g/cm^3, which is typical of coherent silicate rocks (Surkov et al., 1977). Light levels decreased shortly after landing, probably as a result of the spacecraft engines raising dust. Some of the local materials are thus fine-grained and loosely consolidated. Both sites are at an elevation close to 6053 km. Surface temperatures ranged from 730 to 740 K and the pressure ranged from 88 to 94 atm.

Venera 13 landed at 7°S, 303°E on a flat plain at a similar elevation to the Veneras 9 and 10 sites; the Venera 14 site at 13°S, 311°E is at a somewhat lower elevation (fig. 4.3). Both sites resemble the Venera 10 site except that at the Venera 13 site there was a large area of dark regolith close to the spacecraft. Regolith is almost absent at the Venera 14 site and layering in the outcrops is more obvious (fig. 4.4).

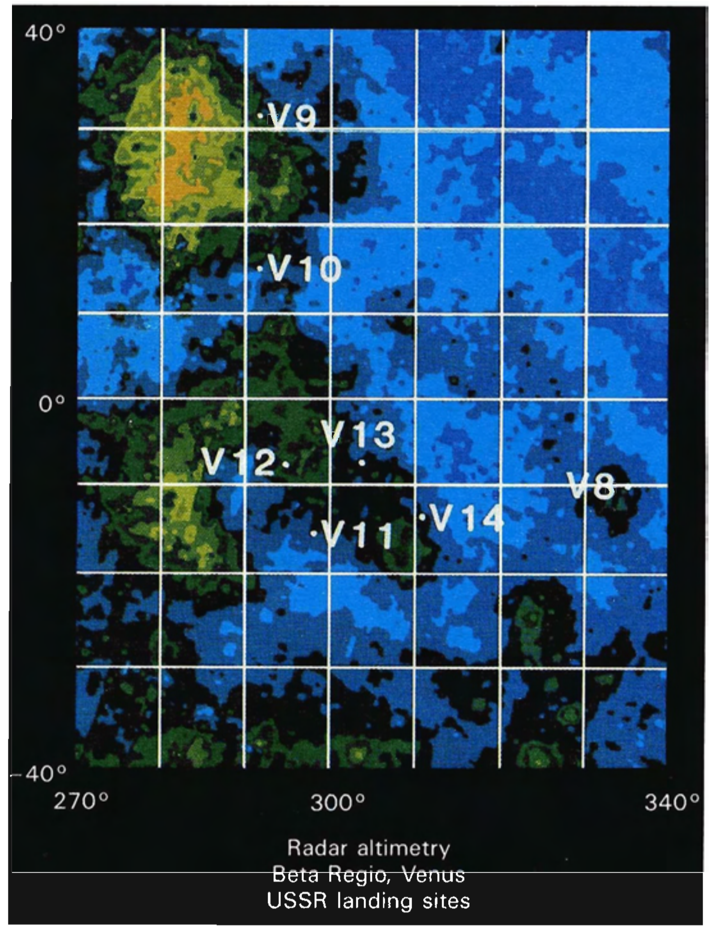

Figure 4.3. Location of the different Venera landing sites. (For key to the color coding of relief, see fig. 4.6.)

The abundances of U, Th, and K suggested by the gamma-ray results of Veneras 8, 9, and 10 (table 4.2) are more similar to those of terrestrial rocks than to those of lunar rocks and meteorites. The Venera 8 abundances are typical of terrestrial continental rocks, whereas the Veneras 9 and 10 abundances more closely approach the values for the terrestrial oceanic crust (see Earth chapter). However, these comparisons should be viewed with caution, for the precisions indicated in table 4.2 may not be a true reflection of the accuracies of the analyses.

More complete chemical analyses were obtained from the X-ray fluorescence instruments on Veneras 13 and 14 (table 4.3). The analyses from both sites are similar except for the K values. They resemble those of terrestrial ocean floor basalts, although the Venera 13 rocks have significantly more K and less Si.

EOLIAN EROSION AND TRANSPORT

At the Veneras 9 and 10 sites surface winds were measured directly by anemometers. They ranged from

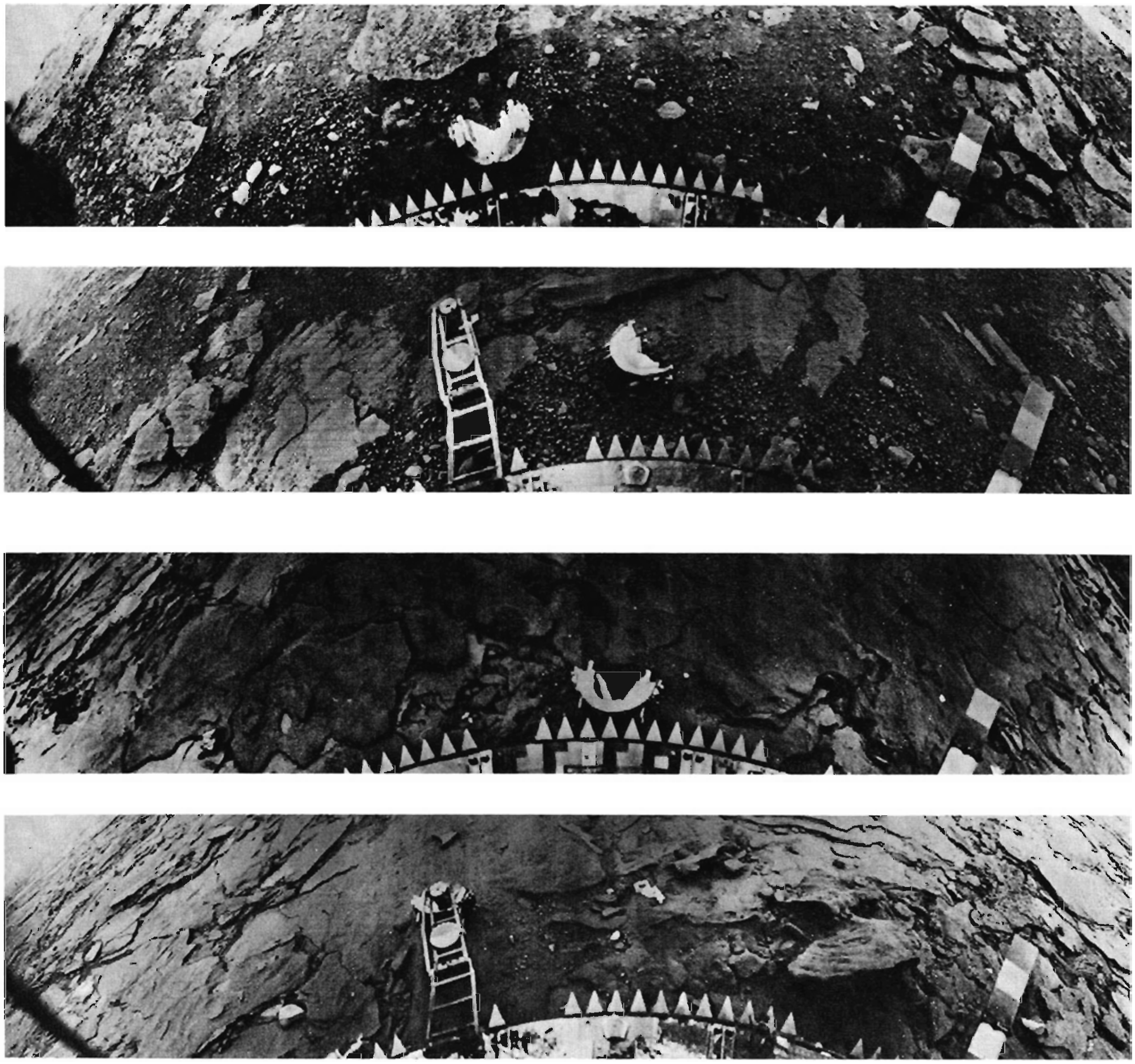

Figure 4.4. Views from the Venera 13 (top) and Venera 14 (bottom) spacecraft. Both spacecraft landed on a level plain with mostly flat, slabby rocks at the surface. The Venera 13 site is also partly covered with a fine-grained regolith.

0.4 to 0.7 m/sec^{-1} at the Venera 9 site and from 0.8 to 1.3 m/sec^{-1} at the Venera 10 site (Keldysh, 1977). In addition, surface winds could be estimated from the tracking of the Venera and Pioneer spacecraft as they descended through the atmosphere. Counselman et al. (1980) showed that the wind profile was similar at all four locations sampled by the Pioneer probes. They ranged from about 100 m/sec at an altitude of 65 km, down to 5 m/sec at an altitude of 10 km, and 1 m/sec at the surface. The dominant motion in the lower atmosphere is retrograde zonal (E–W) rotation. Meridional (N–S) velocities are small throughout the profile and appear to be due mostly to eddies.

These surface winds, though small, are sufficient to raise dust from the surface and to dislodge and move debris. Wind tunnel experiments that simulate Venusian conditions (Williams and Greeley, 1982; Greeley et al., 1982) show that the optimum particle size for wind transport on Venus is 70 μm. The minimum friction wind speed capable of moving particles is about 2 cm/sec (fig. 4.5), close to an order of magnitude less than on the Earth and two orders of magnitude less

Table 4.2. Venera Measurements of Uranium, Thorium, and Potassium Abundances (from Surkov, 1977)

Venera	U($\times 10^{-4}$ wt.%)	Th($\times 10^{-4}$ wt.%)	K(wt.%)	K/U($\times 10^{4}$)
8	2.2 ± 0.7	6.5 ± 0.2	4.0 ± 1.2	+1.65 1.82 −0.85
9	0.60 ± 0.16	3.65 ± 0.42	0.47 ± 0.08	+0.47 0.78 −0.27
10	0.46 ± 0.26	0.70 ± 0.34	0.30 ± 0.16	+1.65 0.65 −0.46

Table 4.3. Composition of Surface Materials at the Venera 13 and 14 Sites on Venus Compared With Terrestrial Oceanic and Continental Crust (from Barsukov, 1982)

Constituent	Venera 13	Venera 14	Terrestrial oceanic basalt	Average continental crust
MgO	10 ± 6	8 ± 4	7.56	2.2
Al_2O_3	16 ± 4	18 ± 4	16.5	16.0
SiO_2	45 ± 3	49 ± 4	51.4	63.3
K_2O	4 ± 0.8	0.2 ± 0.1	1.0	2.9
CaO	7 ± 1.5	10 ± 1.5	9.4	4.1
TiO_2	1.5 ± 0.6	1.2 ± 0.4	1.5	0.6
MnO	0.2 ± 0.1	0.16 ± 0.08	0.26	0.08
FeO	9 ± 3	9 ± 2	12.24	3.5
Total (%)	92.7	95.56	99.86	92.68

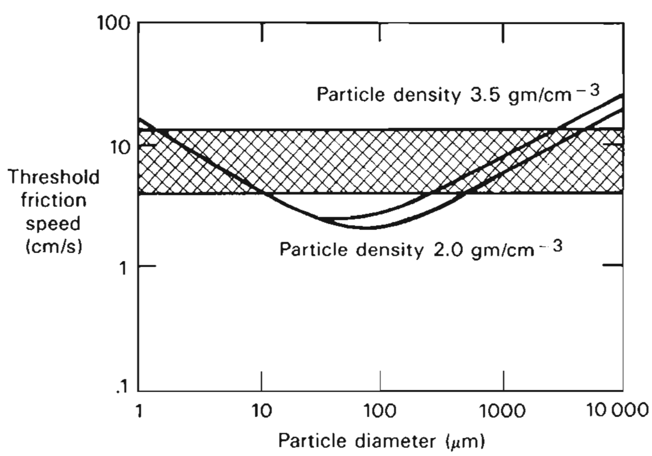

Figure 4.5. The threshold frictional wind speeds required to move particles of different diameters on the Venusian surface. Curves are given for particle densities of 3.5 and 2.0 gm/cm^{-3}, which spans the expected range. The shaded area shows the range of frictional wind velocities expected from the Venera wind data.

than on Mars, a reflection of the high atmospheric density at the Venusian surface. The Venera velocity measurements were made at a height of 1 m above the surface; the frictional wind velocity right at the surface should be about an order of magnitude lower. Thus the Venera measurements imply wind speeds in the 4 to 13 cm/sec range, well above the experimentally derived threshold speed of 2 cm/sec. Theoretical extrapolation of threshold friction speeds as a function of particle diameter to Venusian conditions, based on the work of White et al. (1976) and White (1979), give similar results.

One way in which eolian transport under Venusian conditions appears to differ from Earth and Mars is in the action of the particles after the threshold speeds for saltation are achieved. Particles tend to roll across the surface rather than saltate (Greeley et al., 1982). In other words, their saltation path lengths are very short. This effect which had been predicted on theoretical grounds (White, 1979) must affect the geometry of eolian features such as dunes and ripples. Ripples should, for example, have higher amplitudes and shorter wavelengths than on Earth.

While winds can readily move particulate debris across the Venusian surface, unconsolidated wind-blown debris appears to constitute only a small part of the surface. The dielectric constant of the Venusian surface has been estimated as 4.7 ± 0.8 (Kuzmin and Marov, 1974) which is more consistent with dry rock than poorly consolidated regolith. The dielectric constant of the Moon, for example, ranges from 2.6 to 2.8, a reflection of the presence of a fine-grained regolith. Dielectric constants of rock materials roughly correlate with density, and the range of dielectric constant for the Venusian surface implies densities that range from 1.3 to 3 g/cm^3 with a mean value of 2.2 g/cm^3, which is more consistent with porous rocks than unconsolidated sediments. Although unconsolidated eolian sediments appear to cover only a small fraction of the surface, many of the exposed rocks may be of eolian origin. The densities and dielectric constants are consistent with cemented fragmental debris. The layering observed in the rocks of the Venera sites could be sedimentary. Warner (1980, 1983) suggested that the low-lying dark plains of Venus are eolian sinks, with mostly cemented eolian deposits at the surface.

CHEMICAL WEATHERING

Several attempts have been made to deduce weathering processes at the Venusian surface by searching for plausible reactions that might occur between gases in the atmosphere and normal rock-forming minerals under Venusian conditions. Urey (1952) suggested that the Venus atmosphere might be buffered by the following reaction

$$\underset{\text{wollastonite}}{CaSiO_3} + CO_2 = CaCO_3 + SiO_2$$

The equilibrium pressure for this reaction at 740 K is 90 bars, which is remarkably close to the conditions on the surface. However, as pointed out by Nozette and Lewis (1982), wollastonite is not a common rock-forming mineral and the efficacy of the reaction in buffering the atmosphere is questionable.

The question of how (or if) the Venus atmosphere is buffered is a complex one and intimately coupled with weathering reactions. Rates of reaction between the atmosphere and the surface under the high temperature conditions at the Venusian surface are likely to be high, despite the generally dry conditions. As pointed out by Warner (1983), although the mixing ratio of water vapor in the lower atmosphere, 10^{-3} to 10^{-4}, is up to a factor of 100 lower than in the Earth's atmosphere, the pressure is a factor of 90 higher, so that the partial pressure of water at the surface is about the same on the two planets. Since the temperature is about 450° C higher on Venus, the activity of water is considerably greater. If reaction rates are high, then the rate of fixation of carbon dioxide by reaction with silicates will depend on the rate at which new silicate materials are exposed at the surface by processes such as volcanism, mechanical weathering, and eolian transport. Venus maintains a thick carbon dioxide atmosphere (table 4.4). This could simply be a reflection of extremely low reaction rates of carbon dioxide with silicates at the surface. However, if reaction rates are fast, as has been proposed, then the carbon dioxide must be efficiently recycled back into the atmosphere either by deep-seated processes such as burial followed by volcanism, or by processes at the surface which result in carbon-dioxide-fixing reactions under some conditions, and carbon-dioxide-yielding reactions under other conditions. Several authors have suggested that the lower atmosphere of Venus is complexly buffered and that several gases (H_2O, CO, HF, HCl, SO_2, COS), in addition to CO_2 are buffered by reactions with each other and with the surface. The specific reactions involved are uncertain partly because of the lack of knowledge of the chemistry of the lower atmosphere and the surface rocks. Any equilibrium achieved is likely to be dynamic, depending to some

Table 4.4. Composition of the Atmosphere of Venus (from Nozette and Lewis, 1982)

Species	Mole fraction	Source (6, 7)
CO_2	0.97	Pioneer and Venera
CO	2×10^{-4}	Earth-based
H_2O	2×10^{-5} to 5×10^{-4}	Pioneer and Venera
HCl	$>10^{-6}$	Earth-based
HF	$>10^{-8}$	Earth-based
N_2	0.03	Pioneer and Venera
$SO_2 + S_2$	$<3 \times 10^{-4}$	Pioneer and Venera
H_2S	10^{-6}	Pioneer
COS	$>3 \times 10^{-6}$	Pioneer

extent on the rate of turnover of the surface rocks, and to some extent on reaction rates.

Nozette and Lewis (1982) identified several reactions, involving common rock forming minerals and constituents identified in the lower atmosphere, that could take place at the surface (table 4.5). Some of the reaction could go in opposite directions at different elevations. At high elevations, for example, forsterite reacts with CO_2 to produce magnesite and enstatite but at elevations below 6052 km, where temperatures are higher, magnesite and enstatite recombine, giving off CO_2. Nozette and Lewis suggested that such reversible reactions could contribute to buffering of CO_2 in the atmosphere. In high areas, the surface reacts with the atmosphere to produce weathered products which are removed by creep or by the wind and deposited in the lowlands where the reactions are reversed.

Despite considerable attention given to weathering processes on the Venusian surface, large uncertainties remain, and have little chance of being resolved until better analyses are obtained of the lower atmosphere, and until we have good mineralogical analyses of the surface at various elevations.

GLOBAL TOPOGRAPHY AND SURFACE ROUGHNESS

Because of the near resonance between the rotation period of Venus and Earth's orbital period, the same side of Venus always faces Earth at closest approach. As a result, Earth-based elevation measurements and radar backscatter images are restricted to a limited region—between latitudes 50°S and 75°N, and 130° of longitude between 260° and 30°. Such restrictions do not, of course, apply to spacecraft data, and much of our recent increase in knowledge of planetwide variations in Venus surface properties results from the Pioneer mission. The Pioneer-Venus radar mapper operated at a wavelength of 17 cm and in two modes, altimetry and imaging (Pettengill et al., 1979a). In the altimetry mode, radar reflections from near the subspacecraft point were observed. Signal delay gives a

Table 4.5. Possible weathering reactions on Venus. Reactions marked with an asterisk proceed to the right at high altitudes and to the left in the hotter lowlands. Tremolite may, for example, form at high altitude but break down at low altitude (from Nozette and Lewis, 1982)

$Mg_2SiO_3 + 2CO_2$	$2MgCO_3 + SiO_2$	(1)
forsterite	magnesite quartz	
$Mg_2SiO_4 + CO_2$	$MgCO_3 + MgSiO_3$	(2)*
	enstatite	
$Fe_2SiO_4 + 4\ COS$	$2FeS_2 + SiO_2 + 2CO + 2CO_2$	(3)*
fayalite	pyrite	
$MgSiO_3 + 2HF$	$H_2O + MgF_2 + SiO_2$	(4)
	sellaite	
$CaCO_3 + MgSiO_3 + CO_2$	$CaMg(CO_3)_2 + SiO_2$	(5)
	dolomite	
$2CaAl_2Si_2O_8 + 5MgSiO_3 + SiO_2 + H_2O$	$Ca_2Mg_5Si_8O_{22}(OH)_2 + 2Al_2SiO_5$	(6)*
	tremolite	
$2CaMgSi_2O_6 + 3MgSiO_3 + SiO_2 + H_2O$	$Ca_2Mg_5Si_8O_{22}(OH)_2$	(7)*
diopside		
$KAlSi_3O_8 + 3MgSiO_3 + 2HF$	$KMg_3AlSi_3O_{10}F_2 + 3SiO_2 + H_2O$	(8)*
orthoclase	fluorophlogopite	
$Mg_2SiO_4 + 2CO_2 + SO_2$	$2MgSO_4 + SiO_2 + 2CO$	(9)
$CaAl_2Si_2O_8 + SO_2 + CO_2$	$CaSO_4 + Al_2SiO_5 + SiO_2 + CO$	(10)*
	anhydrite	
$CaMgSi_2Si_2O_6 + SO_2 + CO_2$	$CaSO_4 + MgSiO_3 + SiO_2 + CO$	(11)*
$Mg_2SiO_4 + 1/2CaMgSi_2O_6 + CO_2$	$1/2CaMg(CO_3)_2 + 2MgSiO_3$	(12)*

measure of surface elevation; backscatter efficiency gives an indication of slopes in the meter- to decameter-scale. Elevations were measured to an accuracy of about 200 m. The areal resolution cell ranged from 23 × 7 km to 101 × 101 km, depending on the altitude of the spacecraft during the observations (Pettengill et al., 1979b, 1980). In the imaging mode, the antenna was rotated to observe the surface on either side of the ground track, thereby enabling scattering efficiencies at relatively high angles (30°–58°) to be measured. At these angles scattering by small-scale (cm) roughness elements dominates.

The orbiter started mapping in December 1978 and continued, with some interruptions, until July 1980 (Colin, 1980). For most of the mission, the spacecraft was in a 24 hr orbit with an inclination of 140°; periapsis was maintained at altitudes between 140 and 190 km. As the planet rotated and moved in its orbit, the ground track of the orbiter was offset in longitude by 150 km at the equator. The orbit periapsis, about which most of the measurements were made, completed two and one-half passes around the planet during the course of the mission. On the second or third periapsis passes over the same area, gaps in the previous coverage were filled or new observations interleafed between the previous tracks. The mission data have now been integrated into relief maps (figs. 4.6 and 4.7) and meter-decameter-scale roughness maps, which cover over 90 percent of the planet's surface at a spatial resolution of 100–200 km. Maps have also been compiled of the cm-scale roughness of the area between 10°S and 50°N, at resolutions as low as 30 km (Pettengill et al., 1980, 1982; Masursky et al., 1980).

Much of the Venusian surface is a rolling plain of relatively uniform elevation. As a result, 60 percent of the planet's surface is within 500 m of the modal radius of 6051.1 km; 20 percent is within 125 m (fig. 4.8). Deviations from the modal value are biased heavily toward high elevation; about 20 percent of the surface has an elevation more than 1 km above the modal value, whereas less than 1 percent has elevation more than 1 km below it. The higher areas form a few continental size masses and smaller islands that stand above the global plain. The highest point so far measured (radius of 6062.1 km) is in the Maxwell Montes at 64°N, 2°E. The lowest point measured is in Diana Chasma at 14°S, 156°E, where the planet's radius is 6049.0 km.

The single mode of the elevation histogram for Venus is in sharp contrast to the strongly bimodal distribution of Earth's topography (fig. 4.8, table 4.6). The distributions for all the terrestrial planets have a high elevation tail, a phenomenon that appears to occur at all scales on natural topographic surfaces. On Mars, Earth, and the Moon, the elevation distributions are largely controlled by the various crustal provinces—continents and ocean basins on Earth; uplands and maria on the Moon; lowland plains, cratered uplands, and Tharsis plateau on Mars. The simple elevation distribution for Venus, and the similarity in its skewness to terrestrial continents, suggest a single global crustal province that is topographically similar to Earth's continents. Venus appears to have the same proportion of rugged, youthful mountains as Earth, although the mechanisms that created and modified them may be very different.

Masursky et al. (1980) divided the Venus surface into three major components on the basis of elevation. Their lowland province includes all areas below the reference radius of 6051.0 km and constitutes 27 percent of the surface. The most extensive lowland basin, Atalanta Planitia, centered at 65°N, 165°E is about the size of the Gulf of Mexico. Its surface averages 1.4 km below the datum, and like the surface of most other low areas of the planet, it is sparsely cratered and radar dark. Masursky et al. suggested that these low areas are volcanic plains analagous to the lunar maria, although as already noted, eolian deposits may preferentially accumulate in these low areas and be widely exposed at the surface. Their presence could in part account for scarcity of crater-like dark rings on this unit as compared with the rolling plains.

The second major component of the surface is the rolling plains, which include all those areas with radii between 6051.0 and 6053.0 km, about 65 percent of the planet. The unit is characterized by Root Mean Square slopes of 1°–3° in the meter- to decameter-scale, and probably gently rolling topography at the kilometer scale. Circular features 20–300 km in diameter, with shallow flat floors and radar-bright rims, are more common on this unit than on any other part of the surface. In addition to these crater-like features are several circular radar bright areas, 200–300 km across and up to 1.5 km high. Some have a central dark region of lower elevation and are tentatively interpreted as volcanoes.

The third major component of the surface is the highlands. These occur in three continent-size areas. The first is Ishtar Terra, centered at 70°, 340°E. Its highest part consists of the Maxwell Montes, which

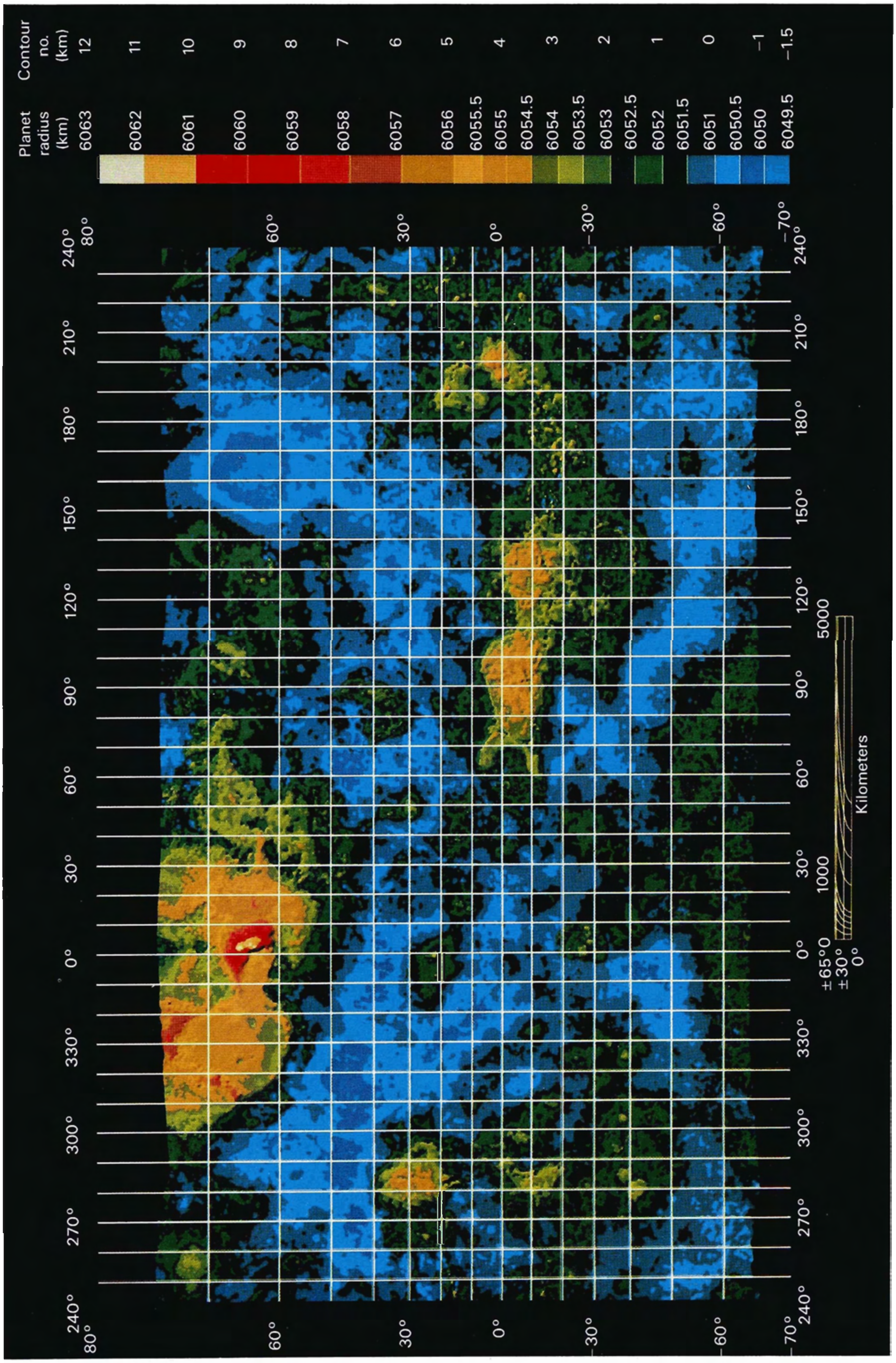

Figure 4.6. A color-coded contour map of elevations of the Venusian surface. High areas are shown in reds and yellows, low areas in blues.

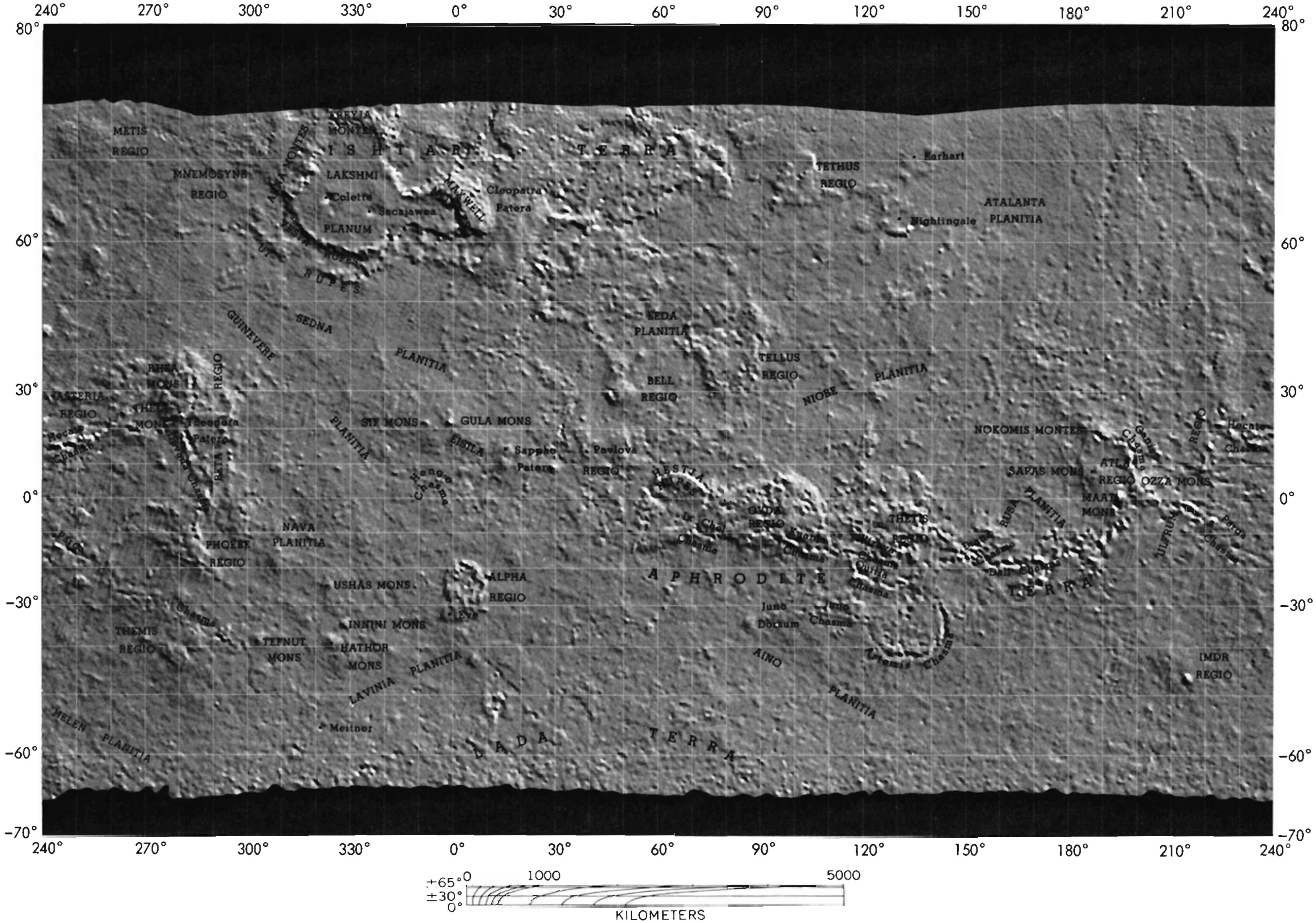

Figure 4.7. The same data as in figure 4.6 but depicted as shaded relief with illumination from the northeast.

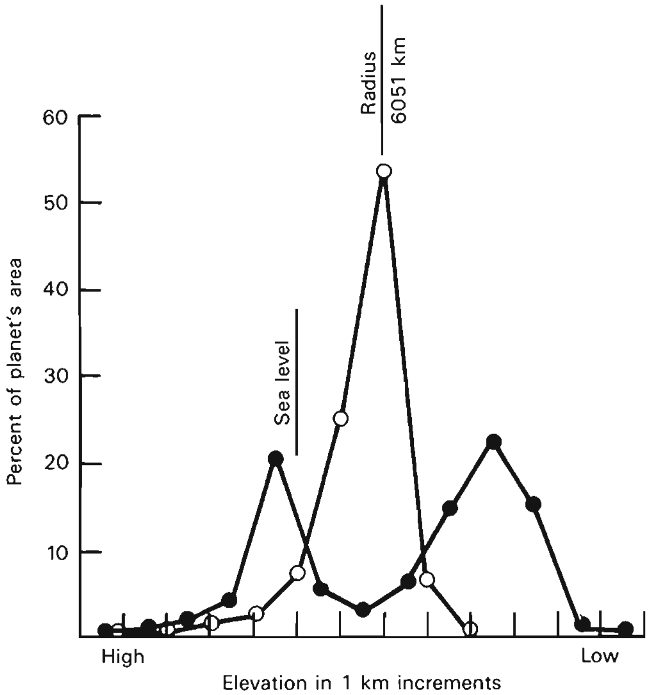

Figure 4.8. Hypsometric curves for Earth and Venus. The curve for the Earth is bimodal with peaks near sea level and at the depths of mature ocean floors. The Venus data are unimodal as skewed toward higher elevations.

extend to heights of 11 km above the datum. The mountains are radar bright and have meter-decameter slopes in the range of 4°–10°; a dark circular feature, possibly a caldera, is situated 2–4 km below the summit. To the west of Maxwell Montes is a dark, roughly circular plain, Lakshmi Planum, standing 4–5 km above the datum. The plain appears to be cratered and is bounded on the south and west by an abrupt, arcuate scarp. Masursky et al. (1980) interpret Lakshmi Planum as an ancient uplifted surface covered with a thin veneer of younger flows. To the east of the Maxwell Montes is some topographically complex terrain, 2–3 km above the datum and consisting of numerous closed depressions with no consistent regional trends.

The second and largest major upland area is Aphrodite Terra, which is about the size of Africa and elongates in a roughly E–W direction between 70° and 210°E just south of the equator. Western and central mountainous regions named Ovda Regio and Thetis Regio, respectively, are separated by a low saddle. South and east of the central mountains are a complex of linear troughs and ridges, the most prominent being the semi-circular Artemis Chasma. The ridges and troughs merge eastward with the mountains of Atla Regio, which mark the eastern end of Aphrodite

Table 4.6. Percentage of Mapped Area of Venus Within Topographic Intervals (from Masursky et al., 1980)

Planetary radii class interval (km)	Percent area in interval	Cumulative percent area in and above interval
6061.9-6061.5	00.004	00.004
6061.5-6061.0	00.005	00.009
6061.0-6060.5	00.007	00.016
6060.5-6060.0	00.006	00.022
6060.0-6059.5	00.010	00.032
6059.5-6059.0	00.008	00.040
6059.0-6058.5	00.010	00.050
6058.5-6058.0	00.007	00.057
6058.0-6057.5	00.013	00.070
6057.5-6057.0	00.016	00.086
6057.0-6056.5	00.047	00.133
6056.5-6056.0	00.106	00.239
6056.0-6055.5	00.327	00.566
6055.5-6055.0	00.594	01.160
6055.0-6054.5	01.106	02.266
6054.5-6054.0	00.965	03.231
6054.0-6053.5	01.692	04.923
6053.5-6053.0	02.440	07.363
6053.0-6052.5	05.376	12.739
6052.5-6052.0	08.982	21.721
6052.0-6051.5	17.376	39.097
6051.5-6051.0	33.664	72.761
6051.0-6050.5	20.533	93.294
6050.5-6050.0	06.091	99.385
6050.0-6049.5	00.607	99.992
6049.5-6049.0	00.008	100.000

Terra. Here the terrain has a dominantly N–S trend, in contrast to the mainly E–W lineaments in the rest of Aphrodite. The eastern mountains are slightly higher (5.7 km above datum) than the western and central mountains (5.5 km above datum). All of Aphrodite exhibits complex patterns of topography, RMS slopes, and backscatter efficiency—patterns that suggest an abundance of steep blocky slopes.

The third major upland region is Beta Regio, centered at 30°N, 285°E. It is composed of two shield-shaped mountains, Theia Mons and Rhea Mons, which reach elevations of 4–5 km above the datum. Both have been interpreted as possible volcanoes (Malin and Saunders, 1977). Smaller elevated areas, Phoebe Regio and Themis Regio, occur to the south of Beta and appear connected to it by a N–S linear disruption zone upon which the two supposed volcanoes lie (McGill et al., 1981).

A vast series of canyons and linear disruption zones connect most of the high ground at low latitudes (fig.

4.9). The largest troughs, the Diana and Dali Chasmata, are 3000–3500 km long and 75–100 km wide (Schaber, 1982). They are part of a broad (1000–1500 km) linear zone of disruption that extends from the west end of Aphrodite through Atla Regio to Beta Regio over 20 000 km to the east. The fracture system thus extends almost three-quarters of the way around the planet in a roughly E–W direction. A second disruption zone, with a prominent rift, Devana Chasma, extends south from Beta Regio at the west end of Aphrodite. The most prominent of all the rifts, the semi-circular Artemis Chasma, does not lie on any of the disruption zones just outlined, but rather lies just to the south of the main E–W system.

SURFACE ROUGHNESS

To first order, roughness correlates strikingly with elevation; elevated regions are much rougher than low regions. This is true, both of the Pioneer-Venus data measured at a wavelength of 17 cm and Earth-based data. Venus is smoother at the centimeter- to meter-scale than the Moon or the rough regions of Mars. Most of the planet has meter-scale RMS slopes between 1° and 3° (Masursky et al., 1980). According to the Apollo bistatic radar experiment, the Moon has slopes of 3° to 4° (Moore et al., 1980; Tyler, 1979). Meter-scale roughness on the Moon is dominated by impact debris. The youngest craters, mostly of Copernican and Eratosthenian age, appear as bright rings in the radar images, but older craters do not, probably because continual break-up of blocks in the floor and rim ejecta reduces the surface roughness. Mars has regions that are much rougher than is typical for Venus, and regions that are perhaps smoother. The volcanic plains in the Tharsis region of Mars, for example, have 10° to 15° slopes, whereas the plains of Elysium and Syrtis Major have slopes of 1° to 2° at 12 cm wavelength (Downs et al., 1973, 1975; Simpson et al., 1978). An aging process that reduces roughness appears to occur both on Mars and the Moon. Older volcanic plains may be smoothed by sand blasting, the removal of weathered products by the wind, and

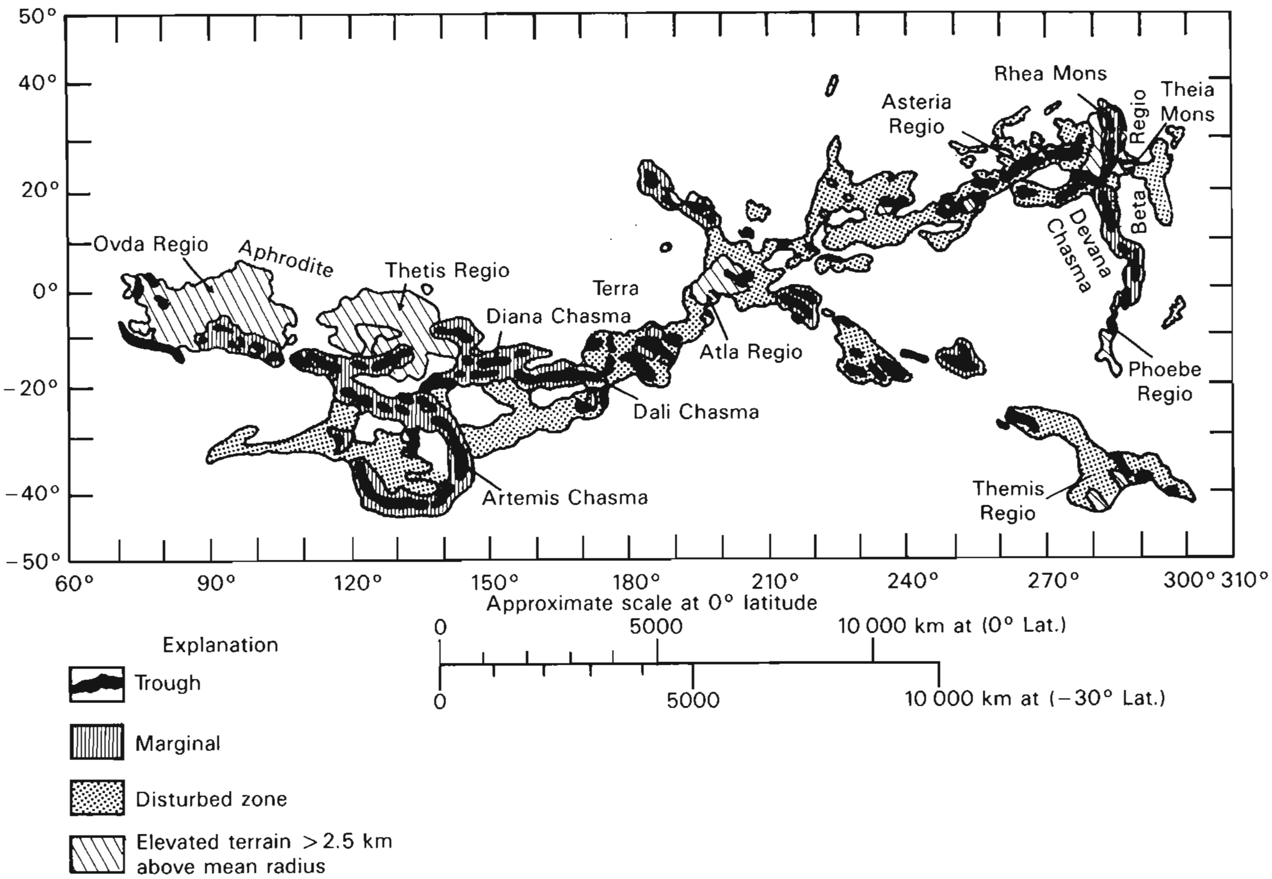

Figure 4.9. Structural sketch map showing interconnected troughs, marginal ridges, disturbed zones, and elevated terrain between Beta Regio and Themis Regio to the east and Aphrodite Terra to the west. The interconnected system stretches in a roughly E–W direction around roughly two-thirds of the planet near the equator (from Schaber, 1982).

through mantling by the products of eolian and chemical processes.

Venus has a wide range of roughness. The highest regions are probably rough, primary volcanic surfaces, but most of the surface has probably been smoothed by weathering and sedimentary mantling as on Mars. Numerous bright circular features have been interpreted as impact craters. If their present size frequency distribution (Campbell and Burns, 1980) represents an equilibrium between crater production and destruction by erosion and sedimentation, then crater obliteration rates of 10^{-5} to 10^{-7} cm/yr are implied, which are more comparable to Mars rates than terrestrial rates.

BRIGHT RADAR RINGS

Bright rings are prominent on many radar images of Venus (Rumsey et al., 1974; Campbell et al., 1979; Goldstein et al., 1976, 1978). They are common on the rolling plains unit but generally absent in the elevated regions. If they are impact craters, then they provide a means of assessing the age of the surface, and the rates of erosion and viscous relaxation of the lithosphere, so that their origin is of crucial importance for understanding the evolution of the surface.

A number of roughly circular bright rings can be seen in Goldstone images of the equatorial region (Rumsey et al., 1974; Goldstein et al., 1976, 1978). The incidence angles are generally less than 6°, and at these angles the backscatter is strongly slope dependent. The ratio of rim width to crater diameter is typical of that for impact craters on other planets, and generally different from that for volcanic features. The bright rings thus appear to be impact craters with raised rims (Saunders and Malin, 1977), but an impact origin is far from proven (McGill et al., 1982). Campbell and Burns (1980) identified 33 bright rings on Arecibo images which generally have higher incidence angles than the Goldstone images, and tend to emphasize variations in backscatter rather than slopes. Several large (>300 km) radar-dark circular features have also been interpreted as impact basins (Masursky et al., 1980).

Thompson et al. (1980, 1981) and Cutts et al. (1981) investigated radar images of lunar craters, and these may provide a basis for interpreting the Venus images. The radar signature of lunar craters is initially a continuous radar-bright region up to 20 times the diameter of the associated crater. Cutts et al. reported that most lunar crater signatures shrink with age rather rapidly until only the crater rim is bright and then this gradually fades. The floor signature has a much greater lifetime than that of the ejecta zone. Radar bright rings are rare on the Moon, and Cutts et al. suggested that they occur only where a crater has been embayed by mare material. This observation might lead to the conclusion that bright-ring features on Venus are volcanically filled craters. However, Cutts et al. suggested a similar result would follow from mantling of rough, radar-bright areas with fine impact debris produced during basin formation.

Saunders et al. (1982) examined the bright ring radar features in 3.8 cm lunar images (Zisk et al., 1974; Thompson, 1974). About 30 radar-bright rings were identified that met the selection criteria that they be complete rings encompassing darker floors and not be at extreme ranges of radar incidence angles. The features found in this study do not occur preferentially on maria, plains, or terra. Somewhat surprisingly, only three of the features have mare-flooded floors. With one exception, an Imbrian crater, all the rings are associated with Copernican and Eratosthenian craters. The diameter distribution of these craters falls along a production curve. Comparison with topography suggests that the inner diameter corresponds to the crater floor diameter, as suggested by Cutts et al. (1981). The outer diameter corresponds to the diameter of the raised crater lip. The implication is that, on the Moon, relatively level areas such as crater floors and the surrounding ejecta deposits quickly become dark to the 3.8 cm radar as a result of impact comminution. Slope appears to be the major contributor to radar brightness.

Saunders et al. (1982) proposed that the evolution of the radar signature of lunar craters is largely slope controlled. Impact craters are initially an extensive radar-bright region. The ejecta and floor become relatively smooth in a short time, but the rim lip and crater walls remain rough until their slopes have been so reduced by erosion that downslope movement of erosion products no longer continuously exposes blocky material.

The processes of crater erosion on Venus are not known. However, it might be expected that, as on the Moon, only a fraction of the total number of circular features is detected, and that their radar signature changes with time as the craters are eroded. The strong correlation between elevation and reflectivity apparent in the Pioneer-Venus data (Pettengill et al.,

1980) suggests that slope is a major factor in controlling backscatter. The radar-bright rings are therefore likely to be caused by steep slopes surrounding a relatively flat circular feature, and impact craters are the most plausible candidates.

If the radar-bright rings are impact craters, then estimates can be made of resurfacing rates on Venus and the ages of different Venusian surfaces. The flux of objects in the size range that would have produced the observed craters has been essentially identical for Earth and Venus, and affected little by the atmosphere (Tauber and Kirk, 1976). Assuming lunar fluxes, Campbell and Burns (1980) estimated from the density of radar-bright rings that the rolling plains have an impact age of 600–800 million years. However, Saunders and Malin (1976) found that the densities varied greatly, and while the plains overall have a crater density that is less by a factor of ten than that of the lunar highlands, densities in small areas may approach those of the lunar highlands. If the rings are of impact origin, the Campbell and Burns "age" is probably a minimum age, being more indicative of the lifetime of the radar-bright signatures than of the surface itself. Presumably older craters that have lost their radar signature could still be present, but remain undetected.

The impact crater hypothesis therefore leads to the supposition that the rolling plains are older than the highland regions and that some of the plains may date back to the decline in impact rates 3.8 billion years ago. Clearly, if a significant fraction of the rings are volcanic, then none of these conclusions are valid. The relative ages of highlands and lowlands remain unknown as well as the absolute ages.

The case for an impact origin for the large (>200 km) dark, quasi-circular features is far less convincing than that for the bright rings. Solomon et al. (1982) recognized two types: (1) circular areas of low radar backscatter and little topographic relief, and (2) large, roughly circular depressions, such as Atalanta Planitia, which is 4000 km across and over 2 km deep. Masursky et al. (1980) likened these dark features to lunar impact basins, and from their size frequently concluded that they were at least 3.8 billion years old. However, Solomon et al., demonstrated that if surface temperatures throughout much of Venus' history were comparable to those that presently prevail, then viscous relaxation would eliminate almost all topographic relief in basins larger than a few hundred kilometers across within 3 billion years. They conclude, therefore, that the large topographic basins, such as Atalanta Planitia, are geologically young and have formed by some process other than impact. One possibility is that they are analagous to terrestrial platform basins, produced by lithospheric extension and thermal subsidence.

GRAVITY

The gravity field of Venus shows strong correlation with topography, large gravity highs coinciding with large topographic highs (Ananda et al., 1980; Sjogren et al., 1980; Phillips et al., 1981; Reasenberg et al., 1981; Esposito et al., 1982). The situation thus differs from that on Earth where gravity is only poorly correlated with the regional-scale topography. The Venusian anomalies are generally smaller than those on the Moon and Mars where 100 mgal anomalies are common. The largest, that associated with Beta Regio, is 135 mgal at a reference altitude of 200 km (Esposito et al., 1982). For comparison, a 500–600 mgal anomaly, referenced to the global mean, occurs over Olympus Mons on Mars.

Simulation of the anomalies that would be produced by the observed topography implies that significant compensation of the topography has taken place. Phillips et al. (1981) attempted to place limits on lithosphere thickness and rigidity by comparing topography and gravity at different wavelengths. They showed that depths of compensation of 100 km or more are required if the topography is supported by density variations alone. If compensation is at shallower depths, then a combination of density differences and flexural rigidity of the lithosphere is required to support the topography. They concluded that, because of creep within the lithosphere, the topography can be supported passively only if it is very young, on the order of 10^7 years, or if the heat flow is considerably less than that on Earth, which they consider unlikely. Another possibility is that the lithosphere is supported dynamically from below, such as by convection beneath the lithosphere (McGill et al., 1981). These conclusions are reinforced by the more recent work of Esposito et al. (1982) who demonstrated that compensation depths of 300–400 km are required to explain the large anomaly over Beta Regio. Weertman (1979), however, questioned the use of terrestrial creep rates in estimating the strength of the Venusian crust. He suggested that, despite the higher temperatures, creep rates in the Venusian lithosphere may be substantially less than in Earth's because of the lower water content.

PLATE TECTONICS ON VENUS

Much of the speculation about the evolution of the Venusian surface has focused on whether plate tectonics have ever occurred on the surface (McGill, 1979; McGill et al., 1982; Phillips et al., 1981; Solomon and Head, 1982). The speculation is triggered by several considerations. First, the similarity in size of Venus and Earth should lead to similar surface heat flows if compositions are comparable. Second, the vast rift systems on Venus could be analogous to the divergent rift zones of Earth. Third, strong correlation of gravity and topography, coupled with some estimates of young crater ages, suggests the topography might be young. Fourth, early chemical analysis of the surface materials, from Venera 8, pointed to the possibility of granitic materials.

Head et al. (1981) and Arvidson and Davies (1981) assessed the likelihood of detecting present-day plate tectonics on Venus solely from the topography. They reconstructed images of Earth using digital terrain data with elements 100 km on a side in order to simulate the Pioneer-Venus resolution. In their simulations many of the diagnostic features of plate tectonics, such as mountain chains and island arcs, disappear. The continents look level and featureless but ocean floor ridges and some trenches are resolved. Arvidson and Davies asserted that a ridge system comparable to the ocean ridges of Earth should be discernible in the existing data even after correcting for the temperature of the Venusian surface and the lack of loading by ocean water. On the other hand, Head et al. (1981) and Solomon and Head (1982) believed several factors in addition to surface temperature and water loading could affect the configuration of the ridges; maintaining that a ridge system could be easily masked on the rolling plains.

Some care must be taken in the application of these analog studies. It is important to understand that the altimeter used by Pioneer-Venus has a horizontal resolution that is determined by the effective length of the pulse. In general, the range that is detected will be that of the nearest surface in the beam. Elevated features tend to be smeared out and depressions such as trenches appear narrower because of the geometric effects of the altimeter system. Experience with radar suggest that the smallest features that can be resolved have dimensions of many radar resolution elements, although linear features may require only three or four depending on how irregular they are.

Other reasons for exercising care in the application of Earth analogs to the interpretation of Venus data is that we do not fully understand the effects of the hydrosphere, atmosphere, and biosphere on Earth's topography. The major fold mountain systems would not appear as they do without the influence of any one of these factors. Of the highest peaks on Earth, the top one hundred or more consist primarily of marine sedimentary rocks.

Phillips et al. (1981) cited differences in profile between the oceanic ridges of Earth and possible counterparts in the Venusian highlands as evidence of their being of different origins. The flanks of the oceanic ridges are concave upward, reflecting contraction by cooling, whereas the elevated areas of Venus, such as Aphrodite and Beta Regio, are convex upward. The ridges of Venus are also convex upward. Kaula (1981) added that the ridges on Venus do not have a narrow distribution about a mode in crest height as do terrestrial oceanic ridges. But both these arguments are relevant only if the Venusian highlands are believed to be the analogs of the terrestrial oceanic ridges, which is doubtful (Solomon and Head, 1982). Furthermore, Brass and Harrison (1982) asserted that the general form and detectability of tectonically created features depend on the balance between erosion rates and rates of plate motion. If erosion rates on Venus are relatively high, linear trenches and rift valleys will fill and not be recognizable.

Theoretical arguments have also been raised against plate tectonics. Anderson (1981) argued that the high surface temperatures will prevent plate tectonics, because the lithosphere can never cool to a low enough temperature to become negatively buoyant. Thus, the currently favored mechanism for driving plate tectonics, drag of negatively buoyant lithosphere into subduction zones, cannot work. Weertman (1979) showed that plate tectonics could occur on Venus only if the rocks were extremely dry, for only then would the lithosphere have the required rigidity at the relatively high Venusian lithosphere temperatures. Finally, Kaula (1981) showed, from the number of possible spreading centers and the dimensions of the observed ridges, that if the ridges formed by spreading, which he doubts, the amounts of internal heat lost through plate tectonics can be no more than 15 percent of the total lost by the planet. On Earth, 70 percent of the internal heat is lost through plate motion.

While acknowledging that plate tectonics are unlikely at present, Phillips et al. (1981) speculated that plate tectonics may have occurred in the past. As we saw above, counts of large craters suggest the rolling plains are ancient, whereas the highlands are relatively young. Phillips et al. suggested that equatorial highlands may have been former zones of divergence, and that at some relatively ancient time in Venus' history, plate tectonics ceased and basalt crusts tended to accumulate over the former divergent zones to form the relatively young equatorial highlands. Possible causes for cessation of plate motion are crustal thickening, loss of water from the interior, destabilization of water at the surface, and rise in surface temperatures as the extreme greenhouse developed.

Kaula (1981) compared the evolution of Venus with that of other terrestrial planets. He noted that on the basis of size and composition Venus might be expected to have evolved along a path similar to Earth. Yet, Venus is more Mars-like than Earth-like. He suggested that the contrast between Earth and Venus is largely due to the thicker atmosphere and consequent higher surface temperatures. These result in a greater depth to the basalt-eclogite transition, which in turn inhibits recycling of the crust. Venus has therefore a thicker crust than Earth, which coupled with the higher surface temperatures, increases the buoyancy of the lithosphere and prevents subduction.

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