THE GEOLOGY OF VENUS

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1. Introduction

The nature of the surface of Venus is one of the keys to answering fundamental questions about the origin and evolution of the terrestrial planets and is of critical significance to comparative planetology. The last 25 years of solar system exploration have provided unprecedented views of the Earth, Moon, Mars, and Mercury. These views have shown that the smaller terrestrial planetary bodies (those one half the radius of the Earth or less: the Moon, Mercury, and Mars) are characterized by globally continuous, unsegmented lithospheres that stabilized very early in the history of the solar system and by ancient surfaces that preserve the several-billion-year-old record of early heavy bombardment and early heating and volcanism (Head & Solomon 1981). In contrast, the Earth is characterized by a globally segmented, laterally moving lithosphere, which is created at divergent plate boundaries and destroyed at convergent plate boundaries. Movement is measured in centimeters per year, and the average age of the surface of the planet is less than 2 b.y. Plate tectonics and plate recycling are fundamental mechanisms of heat loss for the Earth, in contrast to conduction, which is the dominant mechanism for the smaller, one-plate planetary bodies (Solomon & Head 1982). What are the reasons for these differences? Is size, or perhaps position in the solar system and initial conditions, the key? Venus, which is approximately the same size and density as Earth and is the closest planet to Earth, offers an opportunity to test these ideas.
The dense cloud cover of Venus has kept global and regional visible-wavelength panoramas of its surface from view, however, and until the development of high-resolution Earth-based radar telescopes and orbital radar altimetry and imaging systems, the geological nature of the surface of Venus had literally been a mystery. Over the last few years, data have been accumulating and a picture of the nature of the surface of Venus is very slowly emerging (McGill et al 1983, Florensky et al 1983a, Surkov 1983, Phillips & Malin 1983). Recent missions have provided global low-resolution data on the general surface characteristics (Pettengill et al 1980), and local high-resolution images have begun to provide a sense of the geologic structure of parts of the planet (Campbell et al 1983, 1984), as well as detailed panoramas and chemical composition measurements of the actual surface materials (Florensky et al 1983b, Surkov et al 1984). The most exciting developments in the last several years have been (a) the Venera 15/16 imaging radar missions (Kotelnikov et al 1984), which have provided high-resolution imaging coverage of the northern mid- to high latitudes (approximately 20–25% of the planet); (b) the continuing analysis of the Earth-based radar data; (c) the new discoveries from the Pioneer-Venus data; and (d) the new chemical data from the Vega 1 and 2 landers. This review summarizes the emerging picture of the characteristics of the surface of Venus from these data and provides a progress report on the nature and significance of geological processes operating there. We conclude with an assessment of the type of information necessary to complete this emerging picture, so that the themes of terrestrial planet formation and evolution can be understood.

2. **Global Characteristics, Composition, and the Nature of Local Surfaces**

The Pioneer-Venus mission radar experiment obtained near-global data for the surface of Venus, from which altimetry, roughness, and reflectivity values have been determined at approximately 100-km average horizontal resolution (Figure 1). On the basis of these data, the following features were established: global hypsometry (Venus is distinctly unimodal in contrast to the bimodality of the Earth), the major physiographic provinces [Venus can be subdivided into lowlands (about 27% of the surface), rolling uplands (about 65%), and highlands (about 8%)], and the distribution of areas of anomalous roughness and reflectivity (Pettengill et al 1980, Masursky et al 1980, Garvin et al 1985).

Using these three data sets, map units were compiled and their characteristics were interpreted in terms of geological processes and the nature of the surface (Head et al 1985). It appears that the vast majority of the surface of Venus is made up of regionally contiguous block-covered and
Figure 1  Reference map of Venus, showing the geographic location of various features mentioned in the text. The lowlands are indicated by oblique ruling, the rolling plains by white areas, and the highlands by stippled and black patterns (Masursky et al 1980). The black pattern indicates the location of the highest mountainous regions in the highlands (those regions in excess of 4 km above the mean planetary radius of 6051.0 km).
bedrock surfaces, while less than one fourth of the surface contains porous and unconsolidated soil-like material. The distribution of soil-like deposits does not support the presence of large areas of ancient, impact-produced regolith or regional pyroclastic deposits. A small percentage of the surface is characterized by very high dielectric materials. These areas occur predominantly at high altitudes in regions interpreted to be of both tectonic (Maxwell Montes) and volcanic (Rhea and Theia Mons in Beta Regio) origin, but they also occur at lower elevations in patterns indicating a possible volcanic flow origin (Head et al 1985).

The nature and distribution of regional topographic slopes have been analyzed and compared with those of the Earth (Sharpton & Head 1985, 1986). Although regional slopes on the Earth and Venus span the same range (0–2.4°), the slope frequency distributions are distinctly different, with Earth characterized by an excess of extremely low slopes due to abundant regions of planation and deposition. Venus has a distinct peak in slope frequency at about 0.09°, probably related to the lack of atmospheric/hydrospheric erosional processes and associated planation and deposition as seen on Earth. Approximately twice as much of the Earth’s surface is characterized by slopes in excess of 0.24° as Venus', a difference primarily attributable to the presence of continental margins on Earth. The regional distribution of slopes shows that highland areas of Venus are different, with Ishtar Terra characterized by steep bounding slopes, and Aphrodite Terra by more symmetrical, generally shallower slopes.

The series of Soviet Venera lander missions provided insight into the nature of the surface of Venus at a local scale from the point of view of imaging and surface composition. Chemical analyses of surface materials at several landing sites have been interpreted in terms of terrestrial mafic rocks with normal alkalinity, such as tholeiitic basalts or gabbros (Surkov et al 1987, Barsukov et al 1982, 1986a). At two sites the composition of the surface suggests the presence of more differentiated material close in composition to terrestrial subalkaline basaltoids (Venera 13) and perhaps similar to syenites (Venera 8). The work of C. P. Florensky and his colleagues characterized the geology of the surface of Venus and showed that it was dominated by blocks and a layered or laminated pavement (interpreted to be of erosional, duricrust, or pyroclastic origin), with small amounts of surface soil cover (Florensky et al 1977, 1983a,b). Additional studies interpreted the pavement to be of volcanic lava-flow origin (Garvin et al 1984). In a recent joint study between Soviet and US investigators (Pieters et al 1986), multispectral images of the basaltic surface of Venus obtained by Venera 13 were processed to remove the effects of the orange-colored incident radiation resulting from interactions with the thick atmosphere. At visible wavelengths, the surface of Venus is shown to be dark
and without significant color. High-temperature laboratory reflectance spectra of basaltic materials indicate that these results are consistent with either ferric or ferrous mineral assemblages. A high reflectance in the near-infrared observed for neighboring Venera 9 and 10 sites, however, suggests that the basaltic surface material contains ferric minerals and thus may be relatively oxidized.

3. **Regional Distribution of Units: Venera 15/16 Results**

Acquisition of high-resolution radar images by the Soviet Venera 15/16 spacecraft (Kotelnikov et al 1984) permitted the geologic characterization of the topographic features revealed by the Pioneer-Venus data (Figure 2) and an understanding of their regional distribution for the northern mid- to high latitudes (Barsukov et al 1986b, Basilevsky et al 1986). The Venera 15/16 data, in conjunction with the high-resolution Earth-based data (e.g. Campbell et al 1983, 1984, Stofan et al 1987a), revealed the presence of abundant volcanism, extremely complex tectonic deformation, unusual large ovoidal features of apparent volcano-tectonic origin, and an impact crater density providing an estimated age for the northern part of Venus of 0.5 to 1.0 b.y. (Ivanov et al 1986). Correlation of the Venera 15/16 geologic map and the Pioneer-Venus data permitted the derivation of roughness and reflectivity characteristics for the geologic units (Bindschadler & Head 1986a,b). Over 70% of the surface imaged by Venera 15/16 consists of plains units interpreted to be of volcanic origin, while about 25% of the surface is characterized by highly deformed units of tectonic origin (Barsukov et al 1986b, Basilevsky et al 1986, Bindschadler & Head 1987). In the next section we review the characteristics of geologic processes interpreted from these data.

4. **Evidence for Geological Processes**

On the basis of available data, several types of geological processes can be identified as presently acting or having previously acted on Venus: volcanism, tectonism, impact cratering, gravity-induced downslope movement of surface material, eolian erosion/sedimentation, and chemical weathering.

Volcanism is evidently responsible for the formation of the venusian plains, i.e. for over 70% of Venus' surface. Venera 15/16 and Arecibo Observatory radar images of venusian plains display many radar-bright and radar-dark flowlike features up to 100–200 km long (Figure 3a,b). Their morphology and association with some volcanic centers (calderalike depressions, domes, constructs) and fault zones leave little doubt that they are solidified lava flows of relatively low viscosity (Barsukov et al 1984, 1985a,b, 1986b, Pronin 1986, Pronin et al 1986) typical of plains-forming
basaltic volcanism. This morphologic evidence is in good accordance with the previously discussed basaltic composition of the surface determined at the landing sites of the Venera 10, 13, and 14, and Vega 1 and 2 spaceprobes. The plains are evidently composed of a sequence of basaltic flows with some admixture of basaltic debris having eolian and/or pyroclastic origin.
In many places on the plains, numerous domes are observed with diameters of several to 15–20 km (Figure 3b), and a summit crater can be seen on the top of some of them. Spatial distribution of the domes is irregular (Slyuta et al 1987). Clusters of domes alternate with dome-free areas, indicating that their presence is not a required aspect of plains-forming volcanism.

Within the plains, Venera 15/16 images also show several tens of generally circular, gently sloping rises, 50 to 300 km in diameter and usually less than 1 km in height (Figures 2, 4). These structures have summit craters and calderas and also sometimes display radial systems of flowlike features. These characteristics suggest an origin as shield volcanoes. Theoretical considerations of volcanic processes in the Venus environment lead to the predictions that there will be less cooling of magma in the final stages of ascent and that once the magma reaches the surface, convective heat losses will be much more important than in the subaerial terrestrial environment because of the high atmospheric gas density. There appear to be no reasons, however, to expect large systematic differences between lava-flow morphologies on Venus and on Earth. On the other hand, conditions on Venus will tend to inhibit the subsurface exsolution of volatiles, and pyroclastic eruptions involving continuous magma disruption by gas bubble growth may not occur at all unless the exsolved magma volatile content exceeds several weight percent (Head & Wilson 1986).

In addition to the domes and larger constructs mentioned above, the venusian plains are often complicated by narrow (up to 10–25 km), linear features (low ridges, shallow grooves, radar-bright bands of unclear nature), as well as impact craters and buttes of parquetlike terrain. Combinations of these landforms are responsible for the morphological variability of venusian plains. Barsukov et al (1986b) classified the plains into several types: (a) ridge-and-band plains, (b) band-and-ring plains, (c) patchy rolling plains, (d) dome-and-butte plains, and (e) smooth plains. The age relations of plains belonging to the various types are not yet clear, and more analysis is required. The average crater retention age of venusian plains within the Venera 15/16 survey area is about 1 b.y. (Ivanov et al 1986).

Tectonic processes on Venus are interpreted from consideration of elevation and morphologic characteristics available from Pioneer-Venus and Venera 15/16 radar surveys and from Arecibo and Goldstone Station Earth-based radar observations. On the basis of these data, four partly overlapping groups of terrains whose origin is evidently due to tectonism (or a combination of tectonism and volcanism) can be tentatively distinguished within the region surveyed by Venera 15/16.
The first group is represented by tesseræ (tiles in Greek), also often informally called "parquet" terrain. Tesseræ are uplands whose morphology is dominated by densely packed systems of ridges and grooves transecting each other in diagonal, chevronlike, orthogonal, and/or chaotic manner (Figure 5). Typical ridge crest-to-crest spacing is about 5 to 20 km. The height of individual ridges over their base is no more than several hundred meters. Within the Venera 15/16 coverage, terrain of this type is mostly concentrated within the Ishtar Terra highlands [Tessera Fortuna (about 4000 by 1500 km), Tessera Laima (about 2000 by 1500 km), and several smaller features] and in some other uplands nearby (Tellus Regio, Tethus Regio). Taken together, the Venera 15/16 and Pioneer Venus data suggest a wide distribution of tesserae within the upland area outside Venera 15/16 coverage (Kreslavsky et al 1987). The morphology of this terrain seems to be related to deformation acting over broad areas, with stress and/or strain having predominantly horizontal components. The origin of the deformation is still controversial. Gravitational spreading of a surface layer of upraised areas (Sukhanov 1986), dragging of the base of the lithosphere by asthenospheric currents (Basilevsky 1986, Pronin, 1986), and general gravitational relaxation processes (Bindschadler et al 1987) have been proposed as mechanisms.

The second group (Figure 6) is represented by terrain whose morphology is dominated by systems of subparallel ridges and grooves. Their typical spacing is 5 to 20 km, and heights of individual ridges are typically no more than several hundred meters, similar to the tesserae mentioned above. This group is tentatively subdivided into two subgroups. Subgroup 1 (Figure 6a) is a system of subparallel ridges and grooves surrounding the upland of Lakshmi Planum and forming the highland mountain belts of Maxwell, Freyja, and Akna that stand above the adjacent plateau by several kilometers (Campbell et al 1983, Pronin et al 1986). Detailed analysis of Akna and Freyja Montes revealed the presence of anticlines and synclines, thrust faults, and strike-slip faults, and these characteristics were interpreted by Crumpler et al (1986) to indicate the presence of orogenic belts on Venus. The more equidimensional shape of Maxwell Montes has been interpreted to be due to several stages of deformation in

Figure 3 Volcanic plains. (a) Arecibo Observatory radar image of volcanic plains in Guinevere Planitia, southeast of Ishtar Terra. Arrow 1 points to a radar-bright oval feature about 200 km in length. A series of radar-dark flowlike features emerge from the center and extend into and merge with the surrounding plains. Arrow 2 indicates another area that appears to be a center of radar-dark, flowlike features. (b) Venera 15/16 image of western Atalanta Planitia (part of quadrangle 15-11), showing plains and abundant domes and cones. Image is 500 km in width. Scale in kilometers.
Figure 4  Venera 15/16 image (part of quadrangle 4-32) of Collette, a volcanic construct and caldera on Lakshmi Planum in Ishtar Terra. The oval calderalike structure is about 100 by 200 km, is about 1-3 km deep, and has a rim that rises less than 2 km above the surrounding plains. Numerous radar-bright and dark flowlike features extend away from Collette and flow for several hundreds of kilometers toward the surrounding plains.

which the banded terrain is offset by right-lateral movement along linear strike-slip faults, with offset over distances measured in the tens of kilometers (Vorder Bruegge et al 1985, 1986). Retrodeformation suggests that Maxwell had an original shape that was more linear, like that of Akna and Freyja, but that north-south compressional stress and strike-slip movement deformed it into its present form. The combined data in the Ishtar Terra region suggest that there is large-scale tectonic convergence and crustal thickening occurring there (Head 1986). An alternate view holds that the deformation is due to the local lateral displacement related to hotspot plumes centered in the Lakshmi Planum region (Pronin et al 1986).

Subgroup 2 (Figure 6b) is represented by ridge-and-groove belts on the
Figure 5 A section of tesserae, or “parquet” terrain, in central Tellus Regio, showing the complex patterns of deformation. The width of the Venera 15/16 subquadrangle (24-23) is 1000 km. Topographic contours are shown at 500-m contour interval.

plains. They are mostly abundant within the longitude range 150–230°, forming an approximately rhomboidal network (Figure 2) with about 300 to 500 km belt-to-belt spacing. Ridges and grooves within these belts are very similar to those in the highland mountain belts in their morphology, vertical amplitude, and spacing. The elevation of subgroup 2 ridge-and-groove belts above the surrounding plains is usually not more than several hundred meters, and in some cases they are even located within shallow troughs. In earlier publications, ridge-and-groove belts of both subgroups were considered as of compressional origin, resembling in some degree terrestrial folded belts (Barsukov et al 1984, 1985a,b, 1986b, Crumpler et al 1986). Subsequently, some workers have proposed that the belts of subgroup 2 may be extensional features formed by stretching and linear diapirism (Sukhanov & Pronin 1987).

The third group is represented by circular features, mainly so-called coronae for which the term ovoids is also used (Figure 7). These are ring-like systems of essentially concentric subparallel ridges and grooves generally higher than the surrounding plains. Sometimes radial features are also present in addition to the concentric pattern. The diameter of these rings ranges from 150 to 600 km. The morphology, vertical amplitude, and
Figure 6  Terrain showing subparallel ridges and grooves. Subgroup 1 (highland mountain belts) is exemplified by Akna Montes, shown in (a). Here, parallel ridges are concentrated in the high topography of the mountain belt rising several kilometers above the surrounding plain and have been interpreted to be of compressional origin, comprising a component of orogenic belts (Crumpler et al. 1986) (portion of quadrangle 4-32; width of image is 650 km). Examples of subgroup 2 (ridges and grooves) are shown in (b) and are characterized by parallel ridges and grooves that form in belts up to several hundred kilometers wide, extending across the surface for many hundreds of kilometers (quadrangle 12-23; width is 1000 km). These features have been interpreted to be of extensional or compressional origin by different workers. Topographic contours are shown at 500-m contour interval.
Figure 7 Two different types of coronae or ovoids. In the lower left is Anahit Corona, 400–500 km in diameter and showing an annulus of concentric ridges and a variety of surrounding flowlike features. Pomona Corona, in the upper right-hand area, has a distinctive radial pattern of grooves and ridges, as well as a more subdued concentric annulus. The width of the Venera 15/16 subquadrangle 3-13 is 1000 km.

Spacing of ridges within these ringlike systems are mostly similar to those in the previously discussed ridge belts. The area inside the rings is usually lower in elevation than the surrounding ring and distinguished by somewhat chaotic morphology. As the coronae decrease in diameter they merge more or less gradually into another species of ringlike features, the so-called arachnoids, which are 50 to 200 km in diameter and are made up of concentric and concentric-radial systems of narrow ridges. At the larger end of the diameter range, the structure of Lakshmi Planum together with the surrounding ridge-and-groove mountain belts may be considered as a megacorona. The origin of coronae may be related to updoming over upwelling plumes or mantle diapirs, surficial deformation on the flank of the uprising, and subsequent collapse of the core. Stofan & Head (1986) have outlined a range of possible origins of coronae and have investigated gravitational relaxation and diapiric models for their origin and evolution. The origin of arachnoids is not clear.

The fourth group of terrains is represented by large uplands that display predominantly plainslike surface morphology and have systems of sub-
parallel grooves and scarps along their crests. Within the Venera 15/16 coverage, this type of terrain is exemplified by Beta, Bell, and Ulfrum Regiones (Figures 1, 2). The elevation, morphology, and structure of these features leave little doubt that they result from rifting associated with tectonic updoming, or construction and loading. High-resolution images from the Arecibo Observatory revealed the detailed structure of Beta Regio and showed that the central linear depression is a rift zone several hundred kilometers wide containing multiple linear faults spaced 10–20 km apart within it (Campbell et al. 1984). Volcanism is also associated with the rifting, and Theia Mons in Beta Regio is seen to be a large shield volcano that is superposed on the western bounding fault of the rift, partly flooding the rift valley. Further analysis of these data shows the relationships between the Arecibo images and the Venera 15/16 coverage in the northern part of Beta (Figure 8). Based on the full pattern of faults revealed by these two data sets, it seems that uplift has been a dominant process in the formation of Beta Regio (Stofan et al. 1987b).

Aphrodite Terra (Figure 1), which is not covered by the Venera 15/16 data, is the largest highlands region on the planet and is characterized by large linear troughs interpreted to be of extensional origin (Schaber 1982). Detailed mapping of the Pioneer-Venus topography and imaging, as well as high-resolution Arecibo altimetry, has revealed the presence of major linear discontinuities striking across the topographic trend of Aphrodite (Figure 9). These features are several thousand kilometers long, strike N20°W, are parallel to one another, are separated by distances of 200–800 km, and are the location of sharp topographic discontinuities (Crumpler et al. 1987). The characteristics of these features are similar to fracture zones and transform faults found in the terrestrial oceanic crustal environment. In addition, topographic profiles taken between but parallel to the discontinuities are highly symmetrical in broad form around a central axial high and also contain mirror-image shorter wavelength topographic elements across the high (Figure 9; Crumpler & Head 1987). On the basis of these observations and the comparison of many of the features of Aphrodite and terrestrial oceanic divergent plate boundaries, Aphrodite Terra appears to mark the location of extensional deformation and possible crustal spreading on Venus (Head & Crumpler 1987). According to Kreslavsky et al. (1987), parts of western Aphrodite may be composed of tesseralike terrain.

The detailed mapping of the nature and spacing of many of the tectonic features described above and the recognition of two scales of deformation (about 100–300 km and 10–20 km) suggest that these length scales may be controlled by dominant wavelengths resulting from unstable compression or extension of the lithosphere. Modeling suggests that these patterns
could result from a lithosphere that at the time of deformation consisted of a crust that was relatively strong near the surface and weak at its base, and an upper mantle that was stronger than or of nearly comparable strength to the upper crust (Zuber 1987).

In summary, the data obtained thus far indicate that both horizontal and vertical tectonic movements are typical for the surface of Venus. The abundance of horizontal deformation is more similar to that observed on Earth than that commonly observed on the smaller terrestrial bodies, i.e. the Moon, Mercury, and Mars. However, for the area mapped by Venera 15/16, the general tectonic style is evidently different than that of the Earth because there appear to be few recognizable analogs of the key elements of global plate tectonics on Earth (e.g. interrelated planet-wide trenches...
Figure 9  Topographic map of Aphrodite Terra (a) showing the location of the linear cross-strike discontinuities (bold lines), the bilateral symmetry of topography parallel to these features (b), and the lines connecting the centers of symmetry (rise crests) within domains between discontinuities (from Crumpler et al 1987, Crumpler & Head 1987).
and island arcs). The recent discoveries in Aphrodite Terra, however, suggest that divergence and crustal spreading may be occurring there (Crumpler & Head 1987, Head & Crumpler 1987). Thus, major remaining questions are linked to the nature and global distribution of tectonic styles on Venus, the manner in which these are linked to heat-transfer mechanisms, the way in which the Venus environment influences tectonic activity, and the similarity or lack of similarity in styles of tectonism on Venus and Earth.

Impact cratering on the venusian surface has been identified based on the morphological similarity of a number of craters observed on Venera 15/16 images with impact craters on other planetary bodies. Within the territory surveyed by Venera 15/16, about 150 craters (8 to 140 km in diameter) with impactlike morphology have been identified (Basilevsky et al 1985, 1987, Ivanov et al 1986, Kryuchkov 1987). They are superimposed upon terrains of all types, and their spatial distribution appears to be relatively even. The size-frequency distribution is unimodal with a mode lying in the 16–22.6 km diameter interval. The left branch of the distribution curve reflects the influence of the atmosphere in destroying projectiles. The right branch corresponds predominantly to the production function. On the basis of Hartmann's (1987) calibration curve, the average age of accumulation of the observed population is estimated as 1.0 ± 0.5 b.y.

The smallest of the craters observed have a bowl-shaped morphology. As the diameter increases, the craters display morphological transitions to knobby bottoms, then to central-peaked, and finally to ringed basins, similar to impact craters on other terrestrial and icy bodies (Florensky et al 1976, Basilevsky 1981, Basilevsky & Ivanov 1982, Basilevsky et al 1983, Pike 1977). Impact craters were subdivided into three classes according to the degree of morphological freshness (Figure 10): Class 1 are the freshest ones, with a surrounding radar-bright halo interpreted to be ejecta; class 2 have no halo, but the primary crater morphology is practically undisturbed; and class 3 have visible traces of modification, which, however, are not sufficient to cast into doubt the impact nature of these features. A large number of craterlike features that have been highly reworked by volcanic and tectonic processes can be seen on the Venera 15/16 images. Part of them may be a population of destroyed impact craters. On the basis of Hartmann's (1987) calibration curve, this population is estimated to have formed approximately between 3 and 1 b.y. ago (Nikolaeva et al 1986).

Gravitational downslope movement is thought to act on venusian slopes as a universal process of relaxation of steep slopes produced by other processes such as tectonics, volcanism, and impact cratering. The absence
Figure 10 Impact craters on Venus. (a) Class 1, fresh crater (Ivka, about 18 km diameter; subquadrangle 4-31) with bright ejecta; (b) class 2, morphologically unmodified crater (left, Osiponko, about 30 km diameter; subquadrangle 4-22) with no bright ejecta, and class 3, morphologically modified crater (right, Vanda, about 30 km diameter; subquadrangle 4-22).
of significant systematic widening of slopes of impact craters belonging to
different morphological (age) classes (Ivanov et al 1986) gives evidence of
the lack of effectiveness of the process in this size range for at least the
time of accumulation of the observed crater population (0.5–1.0 b.y.).
Rock-fragment talus seen on the panorama at the Venera 9 landing site
suggests that downslope movement of fragmental material occurs (Flor-
ensky et al 1983a).

The presence of eolian erosion/sedimentation processes on Venus is
deduced from the observation of loose soil material, which is theoretically
capable of being involved in eolian mobilization and transportation, and
of winds, which are theoretically capable of mobilizing and transporting
this material (Greeley et al 1984). The reality of such transport was effec-
tively demonstrated by TV observations at the Venera 13 landing site.
Several sequential TV pictures showed clearly that a soil clod of several
centimeters in size that was thrown upon the lander’s supporting ring was
gradually removed during the approximately one-hour observation time
(Selivanov et al 1983). Bare soil-free surfaces of local topographic promi-
nences and the presence of soil in the wind-shadow lows observed on
TV panoramas of the Venera 10, 13, and 14 landing sites are evidently the
result of small-scale eolian processes on Venus (Florensky et al 1983a,b,
Basilevsky et al 1986).

Among the features visible on Venera 15/16 images, only one type was
suspected as having an eolian origin: radar-dark spots and bands localized
at the local topographic lows that may imply wind-shadow conditions and
eolian accumulations of loose material (dust?, sand?) (Barsukov et al
1986b). However, these accumulations are often observed in association
with typical volcanic features such as clusters of domes and flowlike
features, indicating that the origin of this radar-dark material may be
volcanic but its distribution over the surface may be at least partly con-
trolled by eolian processes.

Possible indirect evidence of eolian processes seen on Venera 15/16
images is the disappearance of radar-bright halos around impact craters
undergoing the process of morphological maturation. The halos are zones
of impact-induced surface roughness of decimeter-decameter scale and are
present only around the youngest craters, totaling about one fourth of the
crater population (whose total accumulation time is about 1 b.y.). These
observations suggest that the decimeter-decameter roughness is smoothed
out during a time period as long as 100–200 m.y. This leads to an estimation
of an average rate of eolian (?) resurfacing of less than a few centimeters
per million years.

Chemical weathering is another geological process whose presence on
Venus is deduced from fundamental principles rather than from direct
observations. Thermodynamic analysis shows that igneous basaltic mineral assemblages should be unstable in the venusian surface environment (Khodakovsky et al. 1978, 1979, Barsukov et al. 1982, 1986c, Volkov et al. 1986). The estimates indicate that stable mineral associations should involve anhydrite and magnetite. Sulfatization and oxidation may be the main chemical processes on the venusian surface:

\[
\text{CaSiO}_3 + 1.5\text{SO}_2 = \text{CaSO}_4 + \text{SiO}_2 + 0.25\text{S}_2, \tag{1}
\]

\[
3\text{FeSiO}_3 + \text{H}_2\text{O} = \text{Fe}_3\text{O}_4 + 3\text{SiO}_2 + \text{H}_2. \tag{2}
\]

The high content of sulfur measured in the surface material by the Venera 13 and 14 and Vega 2 landers seems to be in accordance with these thermodynamic predictions and may be a result of incorporation of sulfur from atmospheric gases into the weathering products. The kinetics of this weathering is not well known, and this also makes unclear the scale and intensity of these processes on the surface of Venus.

5. Summary

Studies show Venus to be a dynamic planet whose surface is relatively young. (The average age of the observed part is more like that of the Earth than the ages of the smaller terrestrial planetary bodies.) The surface does not appear to be significantly modified by terrestrial-style erosion and deposition, but it is highly modified by volcanic resurfacing and a wide range of tectonic activity. The wide range of tectonic styles and the distribution of tectonic activity indicate that both regional extension/compression and vertical/horizontal tectonic deformation (including possible crustal spreading) operate there. The global distribution and integration of these features, and thus the global tectonic style and mechanisms of heat transfer, are, however, not yet clear.

The high-resolution data from Venera 15/16 have provided a major advance in our understanding of the nature of the surface of Venus, and continued analysis of these data will bring further important advances. The true picture of the global characteristics and distribution of geologic structures and features must await further data, however. The Magellan mission of the National Aeronautics and Space Administration is designed to obtain radar images over 90% of the surface of Venus at a typical resolution of several hundred meters, and this mission is scheduled to fly in the late 1980s. The data from this mission, combined with our emerging view of the planet, will provide global information on the surface of Venus that will be better than that presently available for the Earth. We eagerly anticipate the acquisition of these data, which should help us to better
understand Venus, its relationship to the Earth, and its relevance to the basic themes of comparative planetology.

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