This chapter contains short descriptions of material units and structures observed on the surface of Venus as well as an abbreviated history of discoveries, which led to the current knowledge of this planet’s geology. It is shown that observed units and structures are broadly similar and commonly exhibit similar age sequences in different regions of the planet, although there is debate to what degree these sequences can be integrated into any single global stratigraphic model. There is a broad consensus concerning the recent general geodynamic style of Venus (no plate tectonics), on the dominating role of basaltic volcanism in the observed crust-forming processes, and in significant role of both compressional and extensional tectonic deformation. Also not under debate is that we see the morphologic record of only the last ~1 b.y. (or less) of the history of this planet and that during this time period the role of exogenic resurfacing was very minor. Several important unresolved questions of Venus geology are formulated and suggestions for future missions, which could lead to resolving them are given.

INTRODUCTION

The bulk properties (diameter, mean density) of Venus and Earth do not differ very much. In contrast, the surface environments are very different. The atmosphere of Venus is 96.5% CO$_2$ and at mean elevation this atmosphere has a pressure of 95 bars, and a temperature of 737K. Both pressure and temperature vary significantly with elevation. Venus is entirely shrouded in clouds, and the surface temperature varies only slightly as a function of latitude. Winds near the surface are thus very gentle; capable of transporting fine materials but not very effective as agents of erosion. Liquid water is obviously not possible on the surface, and thus the water-related processes that dominate surface modification on Earth are not active on Venus. Venus exhibits a bewildering array of structural features, in large part because the extreme slowness of erosion and burial results in preservation of structures for geologically long intervals. In an Earth-like surface environment most of these structures would be eroded or buried.

This chapter is intended to provide a description of the surface geology of Venus as background to a brief discussion of our understanding of the evolution of Venus’ crust. This chapter also will provide context for the chapters devoted to the description of the interior and atmosphere of Venus. We briefly describe here the major geological processes responsible for the current state of the surface, as deduced from the available observations, and then consider the issue of surface evolution. We begin with a short review of the history of the study of Venus, noting the major discoveries achieved
at different stages of exploration. Then we consider the current views of the surface structure and evolution. Finally, we summarize the most important findings to date in Venus geology and surface evolution, formulate the important questions to be resolved in future studies, and make suggestions for future measurements and missions necessary to address these issues. The global map of Venus presented in a shaded relief version colored according to altitude levels (Plate 1) provides a guide to the major physiographic components of the planet. More detailed physiographic maps with feature and terrain names are available on: http://planetarynames.wr.usgs.gov/vgrid.html. Figures in the text are mostly portions of Magellan synthetic aperture radar (SAR) images. These and other Magellan images with the maximum available resolution can be found on: http://pdsmaps.wr.usgs.gov/PDS/public/explorer/html/fmapadvdc.htm. Because chapter length for this monograph is strictly limited, we are unable to provide an extended reference list, and thus cite only representative examples of appropriate works.

HISTORY OF VENUS EXPLORATION

Before the era of space science the lack of visible surface features on Venus when viewed through a telescope suggested the presence of dense clouds. Based on incorrect assumption that the clouds were made of water vapor it was believed by some that the surface environment of Venus is similar to warm and humid areas on Earth. In the 1960’s the radio-telescope observations of Venus provided evidence of its very high surface temperature and slow retrograde rotation [e.g., Cruikshank, 1983]. At approximately the same time, Mariner 2, the first successful mission to Venus, measured on flyby a radio brightness consistent with a hot planet surface [Barath et al., 1964]. Then several missions to Venus obtained increasing evidence of a planet unlike the Earth, culminating in 1970 with the Venera 7 mission, the first successful landing on the planet’s surface. Early Earth-based radar observations led to the discovery of large (~1,000–2,000 km across) radar-bright surface features (e.g., Alpha) of unknown origin [e.g., Goldstein, 1965; Goldstein and Ramsey, 1972].

Then a series of Venera and Vega landers acquired key information on the surface: the gamma ray (GRS) and X-ray fluorescence spectrometry (XRFS) showed that contents of potassium, thorium and uranium, as well as a number of petrogenic elements in the surface material (beneath the landers down to a few decimeters depth in the case of GRS analysis, and a few cm$^3$ sample taken by the drilling device in the case of XRFS analysis), are approximately the same as in terrestrial mafic rocks [e.g., Barsukov, 1992; Surkov, 1997]. TV panoramas showed finely layered rocks and soil in local lows (Figure 1). According to a number of other in-situ observations these rocks were easily crushable and thus obviously porous [Florensky et al., 1978; Basilevsky et al., 1985]. Recently, Basilevsky et al. (2004) suggested a hypothesis that this layered material could be deposited from the atmosphere and be composed of partly indurated sediment of the fine fraction of ejecta of upwind impact craters. This hypothesis implies that the source of the sampled material at the Venera sites could be derived from the kilometers-deep subsurface and not necessarily be representative of what we see in Magellan-scale images in the vicinity of the lander as it was considered in earlier publications [e.g., Kargel et al., 1993; Weitz and Basilevsky, 1993].

Very important data were acquired by the Pioneer Venus mission flown in 1978 consisting of four probes and an orbiter. Two results were of particular importance to geology. One was the discovery by one of the probes of the so-called deuterium anomaly, a D/H ratio larger by a factor of 150 than it is in Earth’s oceans [Donahue et al., 1982]. This implies significant hydrogen escape from the planet, suggesting that early in its history Venus could have lost a large amount of water [e.g., Donahue and Russel, 1997]. Some models even suggest the presence of oceans in the early history of Venus [e.g., Kasting et al., 1984; Kasting, 1988; Grinspoon and Bullock, 2003].

Another result of the Pioneer Venus mission important for understanding Venus geology was radar mapping by its orbiter, which provided a nearly global picture of the planet’s topography, gravity and surface roughness characteristics (e.g., Masursky et al., 1980). It was shown that the planet’s surface is dominated by plains with elevations close to the mean planetary radius (Plate 1). Part of the plains (“lowlands”) were correctly interpreted as relatively young basaltic plains, while the “rolling plains” were considered as “ancient” terrain of possibly “granitic” composition. The older age of the rolling plains was deduced from the observation of numerous circular features then considered as possible lava-filled impact basins. As later shown by observations from Venera 15/16 and Magellan, these circular features are so-called coronae (see below) whose abundance does not indicate surface age. The “uplands” were generally correctly interpreted as a result of tectonic and volcanic crustal thickening [e.g., Masursky et al., 1980]. Analysis of the global topography led to the discovery of belts of rifts resembling continental rifts on Earth [McGill et al., 1981; Schaber, 1982].

The next data set of geologic importance was acquired by the Venera 15/16 twin mission (1983–84), which provided synthetic aperture radar (SAR) images with 1–2 km resolution of about 25% of the planet’s surface (Figure 2) [Kotelnikov et al., 1989]. These images, like those mentioned...
Plate 1. Global hypsometric map of Venus based on the Pioneer Venus Orbiter altimetry. Although its coverage at high latitudes is less complete than the later Magellan hypsometric map, it shows almost all major features of the Venusian surface.
below that were acquired by the Magellan mission, provided pictures of the surface very similar to photographic and TV images. The SAR images show the “illumination-shading” effect when slopes looking toward the illumination source (to the radar in the case of SAR images or to the Sun in the case of photographic and TV images) look brighter while the slopes looking in the opposite direction look darker than the horizontal surfaces. Similar to photographic and TV images, SAR images also show differences in the surface brightness not related to the illumination-shading effect but related to the surface reflectivity. In the case of photographic and TV images the brightness variation are due to optical reflectivity (albedo), but in the case of SAR images the variations are due to radar reflectivity which is a combined function of surface roughness (the rougher, the brighter) and surface electromagnetic properties (metallic and semimetallic surfaces look bright). There are some other differences between the visible range and radar images not important for understanding figures of this chapter.

The Venera 15/16 SAR image resolution was sufficient to directly observe many key elements of Venus geology [Barsukov et al., 1986; Basilevsky et al., 1986]. Dominance of volcanic plains was confirmed, as was the presence of indisputable large volcanic constructs. First identified as significant components of Venus geology in this mission were ridge belts, tesserae and coronae (see below). A population of impact craters was found that suggested a mean surface age for the studied area to be 0.5 to 1 b.y. [Ivanov et al., 1986]. These discoveries suggested a planetary geology that is very different from that of Earth. The Magellan mission allowed extending these Venera 15/16 findings to the entire planetary surface.

The Magellan spacecraft arrived in the Venus vicinity in 1990 and orbited the planet through 1994. The mission provided a nearly global radar survey (SAR images of 100–200 m resolution), measurements of altimetry and radiophysical properties, and derived measurements of gravity anomalies [Figure 3; Saunders et al., 1992]. Magellan data showed that

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**Figure 1.** TV panoramas taken at the Venera 9, 10, 13 and 14 landing sites. Finely layered rocks and darker soil are seen. The layered rocks are crushable and porous [Florensky et al., 1978; Basilevsky et al., 1985] and could be ejecta from the upwind craters deposited from the atmosphere. The teeth seen on the spacecraft in the center-lower parts of the Venera 13 and 14 panoramas are 5 cm apart.
the global geology of Venus is generally similar to that found by Venera 15/16, but the better resolution of Magellan images provided more detail, and thus much more information on mechanisms of formation for materials and structures, and on time relations between them. The descriptions of surface features and units that follow are primarily based on Magellan data analysis.

**CURRENT VIEW OF SURFACE FEATURES AND UNITS**

The accumulated results of the space missions and Earth-based observations coupled with laboratory and theoretical work suggest that the surface of Venus is dominated by volcanic landforms, mostly plains, that are slightly, moderately or highly deformed by various tectonic structures. Plains materials compose up to 80% of the surface of Venus. The most widespread of these are called “regional plains”, which occupy 50–60% of the surface and form a background on which are seen material units and structures either superposed on regional plains, or forming inliers of different sizes embayed by the regional plains. The pre-regional plains inliers include tessera terrain as well as moderately to highly deformed varieties of plains. Below we describe some of the main material units and structures.

In this chapter we use the units as they were identified and used by Basilevsky and Head [1998; 2000] for global consideration of Venus geology. Other researchers, describing and/or mapping individual regions identified units appropriate for these regions and based on their approach to this problem. These local units in some publications are close to the global ones [e.g., Ivanov and Head, 2000a] while in others may be partially close and partially different or significantly different [e.g., Brian et al., 2005; Hansen and DeShon, 2000a]. For clarity, describing units we mention these different names. We describe units generally in the order “from older to younger” deduced by many researchers in different regions of the planet. The question how these local stratigraphic columns, reflecting time sequences, can or can not be integrated into a global stratigraphic column is considered in the Discussion part of this chapter.

**Tessera terrain.** This terrain forms “islands” and “continents”, occupying in total ~8% of the surface [Ivanov and Head, 1996]. Tessera exposures stand topographically above the surrounding regional plains. The surface of tessera terrain is very rough, being dissected by numerous criss-crossing ridges and grooves a few km wide and tens of km long (Figure 4). In the place where it was first identified [Barsukov et al., 1996] the tessera tectonic fabric resembles that of the tile roof that later led to the terrain name (tessera = tile in Greek). Ridges are evidently formed by compressional tectonic deformation while many grooves are extensional structures [e.g., Sukhanov, 1992; Ivanov and Head, 1996; Hansen et al., 1997]. The surface of tessera terrain looks bright on the Magellan images, due to high meter-decameter roughness [Ford et al., 1993] that is at least in part a result...
of tectonic deformation. This deformation implies episode(s) of intensive tectonic activity, which formed what we see now as tessera terrain. The composition of tessera material is unknown. Some researchers suggest it has a basaltic composition; others believe that tessera may be made of more feldspathic material resembling to some degree anorthosites on the Moon or granites on Earth [Nikolaeva et al., 1992]. Surrounding plains of apparent volcanic origin embay the tessera [e.g., Basilevsky and Head, 1995, 1998, 2000, Bleamaster and Hansen, 2005; Ivanov and Head, 2001]. In some rare cases, when tessera is in contact with moderately and highly deformed plains, it can be seen that materials composing these plains embay tessera terrain. Because tessera terrain is observed in practically all regions of Venus, this intensive tectonism could be of global or close to global scale, although the data in hand are insufficient to determine if the deformation resulting in the formation of tessera terrain occurred at similar times globally or else at different times in different places.

In the western part of Ishtar Terra, in close association with tessera terrain, are seen Mountain belts, which surround the volcanic plateau Lakshmi [e.g., Barsukov et al., 1986; Basilevsky et al., 1986; Crumpler et al., 1986; Pronin, 1992; Solomon et al., 1992]. They consist of clusters of parallel (within the given belt) ridges (see Figure 2). The mountain belts are among the topographically highest features on Venus. The summit of the highest of them, Maxwell Montes, stands more than 11 km above the mean planetary radius. Parallel ridging and high altitudes of the mountain belts are considered as evidence that they formed due to horizontal compression. These mountain ranges merge laterally into tessera terrain so maybe these two are close in age. As in the case of tessera terrain, the composition of the mountain range material is not known.

The top parts of the mountain ranges (and of some other highlands of Venus as well) have extremely high radar reflectivity, appearing very bright on the Magellan images. This brightening appears above some critical altitude, although the exact value varies somewhat in different parts of the planet. It was suggested by some researchers that above this altitude, surface material has undergone a specific weathering in which the iron in silicates, such as pyroxenes and olivines, is segregated into minerals having a high electric conductivity (iron oxides or sulfides) [Klose et al., 1992; Wood, 1997]. Other researchers however suggested that it could be a temperature-controlled deposition of some heavy metals and/or their sulfides and sulfosalts, whose components sublimed from the surface rocks of the topographically lower and thus hotter regions [Pettengill et al., 1997; Schaefer and Fegley, 2004].

Densely fractured plains are also called by many mappers densely lineated [Campbell and Campbell, 2002; Ivanov and Head, 2004a] or lineated plains [e.g., McGill, 2000]. They are seen in many areas of Venus as relatively small (tens of km to 100–200 km across) “islands” of densely fractured material (that is basis for the unit name) standing a few hundred meters above the surrounding regional plains (Figure 5). If one ignores the fractures, the terrain forming these islands is plains [e.g., Basilevsky and Head, 1998, 2000; Brian et al., 2005]. These islands are generally considered to consist of plains-forming volcanics, probably of basaltic composition, that have been deformed by closely spaced fractures. The structural pattern of the fractures is generally subparallel within a given island. The islands of densely fractured plains are obviously embayed by the regional plains [e.g., Basilevsky and Head, 1998, 2000; Brian et al., 2005; Campbell and Campbell, 2002; McGill, 2000]. In rather rare cases, where they are in contact with tessera terrain, their material seems to embay tessera (Figure 5). A terrain of this type is also observed in many coronae (see below), where radial and concentric structural patterns of dense fracturing are typical. Global abundance of outcrops of the densely fractured plains material is about 3 to 5% [Basilevsky and Head, 2000a].

Ridge belts. Most ridge belts are long, relatively narrow areas that are somewhat elevated above surrounding regional plains (Figure 6). They contain plains-like materials that have been deformed into individual ridges that generally
parallel the long dimensions of the belts. They occur as continuous belts or as patches that appear to be partially flooded by lavas of the surrounding regional plains. The material composing ridge belts is commonly slightly rougher than the material of regional plains, and it probably also consists of basaltic lavas. Folding into relatively broad (3–5 km) ridges arranged into parallel bands is typical of these belts and most likely resulted from horizontal compression. Ridge belts differ from the mountain belts described above in their much lower altitudes (hundreds of meters) and probably in the density of deformational structures. In most observed cases, regional plains embay the belts [e.g., Basilevsky and Head, 1998, 2000; Bridges and McGill, 2002; Ivanov and Head, 2004a] although in some places their age relations are ambiguous [e.g., Rosenberg and McGill, 2001]. Global abundance of ridge belts is about 3 to 5% [Basilevsky and Head, 2000a].

Regional plains. Although studied in detail in the initial Magellanic images [Guest et al., 1992; Head et al., 1992], regional plains were first identified as a specific unit by Basilevsky and Head [1995] under the name of Plains with wrinkle ridges. In that work “Plains with wrinkle ridges” included what is now called Shield plains. In later studies “Plains with wrinkle ridges” and “Shield plains” began to be mapped separately [e.g., Aubele, 1996; Ivanov and Head, 2001]. Many researchers prefer to call the first one “Ridged plains” [e.g., Bridges and McGill, 2002; Campbell and Campbell, 2002] or “Regional plains” [e.g., Brian et al., 2005; McGill, 2000] as we do here. Regional plains occupy 50–60% of the surface [Basilevsky and Head, 2000a]. They have a rather smooth (at the scale of observation) surface (Figure 7), often with flow-like features, which are inferred to be solidified lava flows [Guest et al., 1992; Head et al., 1992]. These plains are deformed by a network of relatively narrow (1–2 km) gently-sloping ridges tens to hundreds of km in length, called “wrinkle ridges”. Wrinkle ridges are the result of “wrinkling” of the surface by moderate horizontal compression [e.g., McGill, 1993]. Large areas occupied by the flow-like features (100–200 km long flows are common) and very gentle slopes, along which the flows were emplaced, indicate high-yield eruptions of low viscosity, probably basaltic, lava which formed plains that were subsequently deformed by wrinkle ridges. The suggestion of basaltic composition of the lava is supported by the analysis of the Magellanic images for the landing ellipses of the Venera/Vega landers. This analysis showed that the landing sites,
where the basaltic composition was measured [Venera 9, 10, 13, Vega 1, 2; Barsukov, 1992; Surkov, 1997], are dominated by regional plains [Abdrakhimov and Basilevsky, 2002]. But if the layered rocks seen in the Venera TV panoramas are sediments of the fine fraction of ejecta from upwind impact craters, as suggested above, these analyses may partly represent other units underlying regional plains.

Within these plains are seen sinuous channels of 2–5 km width and lengths of hundreds of kilometers [Baker et al., 1997]. One of the channels, Baltis Vallis, is 6,800 km long, a distance that is about 1/6 of the circumference of Venus (Figure 7). It is not yet clear how these channels formed, but the channel morphology implies erosion by some liquid. The most popular view is that the channels resulted from thermal and/or mechanical erosion by flowing high-temperature lava, perhaps komatiitic lava. Similar channels (although not so long) are known on the Moon and even smaller analogs are seen on the flanks of some terrestrial volcanoes. The major enigma of the channels on Venus is their great length. Calculations show that the temperature of the surface and near-surface atmosphere is, despite its very high temperature relative to Earth, still cold compared to basaltic or komatiitic lava. Thus komatiitic lava in particular should solidify rather quickly, inhibiting channel formation. Mechanical erosion by liquids having significantly lower melting temperature, such as sulfur or alkaline carbonatite melt, are considered as possible alternatives [e.g., Kargel et al., 1994].

*Shield plains.* These generally form fields of small shields a few hundred kilometers across. Their surface is peppered with numerous gentle-sloping volcanic shields 5 to 15 km in diameter (Figure 8). Coalescing flanks of the shields form most of the plains surface. Different morphologic analyses show that individual shields can predate regional plains, can be coeval with them, or can postdate them. The relative proportions of these pre, syn, and post varieties are a subject of debate. Addington [2001] and Hansen [2005] concluded that most post-date regional plains, whereas Ivanov and Head [2004b] concluded that pre-regional-plains varieties dominate over the syn- and post-regional-plains examples. Most likely the main reason for this disagreement stems from different criteria used for these studies, and different areas of shield plains sampled. Global abundance of shield plains was estimated by Basilevsky and Head [2000a] as close to 10–15%.

The gentle slopes of the shields imply that they are made of low viscosity, probably basaltic lava. The Venera 8 lander, whose landing ellipse is dominated by shield plains, found contents of potassium, uranium and thorium (beneath the lander down to a few decimeters depth) significantly higher than those typical for the majority of terrestrial basalts. This led to the suggestion that some parts of the shield plains are composed of alkaline basalts, or even geochemically more evolved rocks, which would have higher viscosities than normal basalt [Basilevsky, 1997].
**Lobate plains and flows.** These are observed in two partly overlapping varieties. The first one (lobate plains) typically forms fields of individual flows not directly associated with volcanic edifices. The flows are of variable radar brightness, suggesting variability in their surface texture (Figure 9 left). The flows are tens to 200–300 km long and from a few to a few tens of kilometers wide. They typically overlay regional plains and embay other units described above. More than 200 flow fields were observed on the surface of Venus, each with an area larger than 50,000 km² [Crumpler et al., 1997]. Their sources are often associated with rift zones (see below). Some of these young lava flows occur in association with coronae. The great length of the flows on very gentle-sloping surfaces suggests low viscosity of the lava. This, in turn, is usually considered as evidence of basaltic composition.

Lobate flows are also seen associated with volcanic constructs composing the second subunit of the “lobate plains and flows” unit (Figure 9 right). More than a hundred constructs larger than 100 km in diameter and about 300 constructs 20–100 km in diameter are observed on Venus [Crumpler et al., 1997; Magee and Head, 2001]. The youngest lavas related to these constructs are clearly superposed on regional plains. The highest volcano on Venus, Maat Mons, stands about 9 km above mean planetary radius. Lava flows radiating from Maat Mons cover an area about 800 km across. These large and intermediate sized volcanoes are morphologically very similar to basaltic shield volcanoes on Earth, although the latter are typically smaller than their counterparts on Venus. Measurements by the Venera 14 lander, whose landing ellipse is dominated by lava flows associated with the Panina Patera volcanic construct, showed a basaltic composition of the surface material [Barsukov, 1992; Surkov, 1997]. However the TV panoramas of the site show that the material analyzed at this place is represented by finely layered rocks so its source could instead be ejecta of upwind impact craters, and not the Potanina lava flows. Global abundance of the lobate plains and flows unit is estimated to be about 10% [Crumpler et al., 1997; Basilevsky and Head, 2000a,b].

**Smooth plains** on Venus are typically radar dark. They occupy only a few percent of the surface [Basilevsky and Head, 2000a]. Some relatively rare smooth plains have very sharp boundaries. Their morphology and frequent association with obvious volcanic landforms suggest that they are fields of lava flows with very smooth surfaces (Figure 10 left). Another variety of smooth plains has diffuse boundaries and is commonly associated with large impact craters. These are probably mantles of fine debris, the primary source of which is ejecta from impact craters (Figure 10 right).

**Structural units.** Significant tectonic deformation is observed in several units described above and some are so penetratively deformed (tessera and densely fractured...
plains) that their original properties are not evident. But these units are embayed by younger units, so it is logical to consider them as material units. Two types of highly deformed terrain, however, show no (or partial) embayment and according to recommendations of the U.S. Geological Survey [Tanaka, 1994] are mapped by many researches as structural units. They are represented by two overlapping and often closely associated varieties: rifts and fracture belts. Although mapped as structural units by some workers, it is important to note that rifts and fracture belts are not material units in the same sense as are most mappable units on Venus. Their combined global abundance is about 9–10%, of which about 2/3 are young rifts and 1/3 fracture belts [Price, 1995; Basilevsky and Head, 2002b].

Young rifts on Venus are rather similar to continental rifts on Earth and form a global system up to 40,000 km long [Masursky et al., 1980; McGill et al., 1981; Schaber, 1982]. They are typically topographic troughs, whose floors may be a few of kilometers below the neighboring non-rifted terrain, whereas the rims of the troughs are commonly uplifted above the neighboring terrain. The walls and floors of the troughs are fractured, commonly very heavily (Figure 11 left and center). The anastomosing character of the fracturing and significant changes in the width of individual fractures are often typical of rifts. Young rifts cut regional plains. Young post-regional-plains lava fields and volcanic constructs are commonly associated with rifts. They are locally superposed on some elements of rifts but locally are cut by rift faults. The general consensus is that rifts formed in the environment of tectonic extension.

Fracture belts are partly older and partly younger than regional plains [e.g., Hansen et al., 1997; Ivanov and Head, 2001]. They are typically seen as highly fractured areas partly flooded by lavas of regional plains (Figure 11 right) and partly fracturing regional plains. It thus is possible that this relatively old rifting was more extensive than one can judge from the abundance of fracture belts that are now observed. Compared to the younger rifts, fracturing within fracture belts is more homogeneous and less anastomosing.

It is necessary to add that some researchers avoid defining and mapping structural units [e.g., Hansen, 2000; Hansen and DeShon, 2002; Bleamaster and Hansen, 2005]. For example, part of a very heavily tectonized rift zone of Aphrodite Terra (Figure 11 center) instead of being mapped as “rifted terrain” was mapped by Bleamaster and Hansen [2005] as “chasmata flow material”. Their conclusion that it is material of volcanic flows was derived from the following consideration: They assumed that Venus could host only three basic rock types: igneous, metamorphic and sedimentary. Because of “absence of surface water and the paucity of
eolian erosion on Venus” they rejected the suggestion of any significant presence of sedimentary rocks. Because of the absence on this planet of widespread erosion they considered surface exposures of metamorphic and intrusive igneous rocks as not likely. So they conclude that “surface rocks most likely originated as extrusive igneous rocks, that is volcanic flows” (page 2 of the pamphlet accompanying the geologic map of Bleamaster and Hansen [2005]).

Coronae. Several hundred volcanic-tectonic structures called “coronae” (“corona” singular) are observed on the surface of Venus. They were first discovered in the analysis of radar images of Venera 15/16 [Barsukov et al., 1986]. Coronae appear to be unique to Venus. Coronae are oval to circular features typically 100 to 300 km in diameter (Figure 12), although a few are even larger. They have a tectonically deformed annulus, which generally stands a few hundred meters above the surrounding plains. The area inside the annulus is commonly lower than the surrounding plains and partly flooded with plains-forming volcanics. Aprons of young lobate volcanic flows are commonly seen radiating from many coronae. A core is seen at the center of some coronae as an elevated and tectonically deformed area. Coronae are considered to form as a result of rising of hot mantle plumes/diapirs [Basilevsky et al., 1986; Stofan et al., 1997]. The diapir raised the upper lithosphere and crust, and during its ascent produced magmatic melts, some of which reached the surface and formed the corona-associated lava flows. When the diapir cooled, the uplifted surface subsided producing the structure now called a “corona”. Some coronae are scattered among the regional plains. Others form clusters and chains associated with rift zones.

Impact craters. In the Magellan images of Venus more than 960 impact craters from 1.5 to 270 km in diameter were identified [Schaber et al., 1998; Herrick et al., 1997]. Their size frequency distribution is obviously controlled by the screening effect of the massive Venus atmosphere. Most statistical tests show that the distribution of impact craters around the planet is indistinguishable from a random one [Schaber et al., 1992; Phillips et al., 1992; Strom et al., 1994; Kreslavsky, 1996], although some more specific tests suggest the possibility of a partly non-random distribution (see below) [Hauck et al., 1998].

The morphology of impact craters on Venus is essentially similar to that of impact craters on other planets and satellites. They are circular depressions surrounded by an elevated rim (Figure 13). The rim, and the area surrounding it, are knobby and typically radar bright due to a surface layer of relatively rough ejecta excavated from the crater. The general morphology of impact craters on Venus is correlated with their size (Figure 13A, B, C): Craters smaller than 10–20 km in diameter have an irregular floor. Larger craters have a central peak on the floor. Even larger (>50–60 km) craters have a concentrically ringed floor. A similar size dependence (although with different transitional diameters

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Figure 9. Two varieties of lobate flows. Left are flows of the NE part of Mylitta Fluctus lobate plains whose source is Kalaipahoa Linea rift; right are lobate flows of the NW outskirt of Sapas Mons volcano. Both varieties are superposed on regional plains. Magellan images centered at 54°S, 357°E and 10.5°N, 186.5°E correspondingly.
between types) is observed for craters on other planetary bodies. On the other bodies, however, craters of smaller size are not irregular-floored but have a relatively smooth bowl-shaped floor. This difference is due to break-up of relatively small crater-forming projectiles on their way through the massive atmosphere of Venus. The result is that in these cases the planet is impacted not by a single projectile, but a swarm of dispersed fragments.

Around many craters on Venus flow-like features are seen extending from the knobby ejecta (Figure 13D). These features (commonly called “outflows”) are believed to be flows of high-temperature melt produced by the crater-forming impact. Their abundance on Venus is probably due to the higher temperature of the surface of Venus, compared to other planets and satellites, and thus the higher temperature of the upper crust. This would tend to increase the amount of impact melt produced [Schultz, 1992]. Some ejecta outflows show evidence that their material is rather easily redeposited by wind. This suggests that these could be formed by flows of fine-grained material suspended in the air, thus mimicking formation of turbidites flows on the continental slopes of terrestrial oceans.

Radar dark haloes are seen in association with many impact craters on Venus (Figure 13). The haloes are considered due to relatively fine-grained debris deposited as a part of the crater formation process. With increasing time, haloes degrade and disappear, so the presence and prominence of the halo can be used as a measure of crater age [Arvidson et al., 1992; Basilevsky and Head, 2002a; Basilevsky et al., 2003]. Some areally extensive haloes have a parabolic form with the parabola apex pointing to the east (Figure 13E). These dark parabolas are considered to have formed due to delivery of crater ejecta into the upper parts of the atmosphere and consequent settling. During this settling, the fine fraction of the ejecta is entrained by strong zonal winds, which blow at high speed towards the west. The dark parabolas associated with the youngest craters degrade with time into non-parabolic haloes. The total amount of relatively fine debris produced by impacts after formation of the regional plains and widely distributed by the wind is equivalent to a global layer a few meters thick (Garvin, 1990).

**Aeolian features.** In the absence of liquid water on Venus, exogenic resurfacing is dominated by aeolian processes [Greeley et al., 1997]. The orientation of aeolian features is indicative of the dominant directions of near-surface winds and thus can be helpful in studies of the dynamics of the lower atmosphere. Part of the observed aeolian features could be formed by strong winds, which are thought to accompany impact cratering events [Ivanov et al., 1992]. The observed aeolian features are represented by radar-dark mantles, wind streaks, yardangs and dunes. The first two types of aeolian features are rather common on Venus, while the features of the second two types, large enough to be seen on the Magellan images, are observed in only a few localities.

**Figure 10.** Two varieties of smooth plains. Left is the volcanic variety with sharp boundaries observed east of Ohogetsu corona, right is aeolian variety with diffuse boundaries SW of impact crater Mead, whose ejecta probably is the source of aeolian debris. Magellan images centered at 28°S, 84°E and 8°N, 52°E correspondingly.
Dark mantles commonly are seen in association with impact craters, forming halos of different sizes and forms (see above). The source of the dark-mantle material is fine debris formed by crater-forming impacts. In many cases the dark mantles have lost direct contact with impact craters and occupy wind-shadow localities in local topographic lows and behind, or against, positive topographic features, becoming a variety of smooth plains (see above).

Wind streaks are the most abundant aeolian features on Venus. They vary significantly in shape (linear, fan-like, wispy), size (from a few to tens of kilometers), and radar brightness (bright, dark, mixed). Figure 14A, B shows examples of their variety. Wind streaks obviously formed as the result of accumulation and/or erosion of loose surface material due to wind turbulence behind topographic features. It is rather typical that lateral boundaries of wind streaks are diffuse.

Figure 11. Examples of rifts and fracture belt. Left is fragment of the young Ganis Chasma rift composed of anastomosing faults cutting regional plains; center is fragment of the young Jana Chasma rift, saturated with densely spaced faults; right is relatively old fracture belt composed of more homogeneous and less anastomosing faults embayed by regional plains. Magellan images centered at 12°N, 198°E, 12°S, 112°E, and 32°S, 227.5°E correspondingly.

Figure 12. Two examples of coronae. Left, Thourus corona, 6.5°S, 12.9°E, D = 190 km. Its annulus is embayed by regional plains, post-regional-plains activity is very minor; right, Dhorani corona, 8°S, 12.9°E, D = 150 km, showing extended apron of post-regional-plains lava flows. These two examples show that morphologically observable activity of some coronae terminated before the emplacement of adjacent regional plains (Thourus) while activity of others continued after the regional plains emplacement (Dhorani).
A field of possible yardangs, which are wind-erosional ridges, is observed in the vicinity of the crater Mead, the largest impact crater on Venus. They are represented by sets of parallel, linear, slightly sinuous grooves and ridges separating them (Figure 14D). Yardangs differ from wind streaks in that they have well-defined boundaries and lack a distinctive relation to topographic features, such as hills.

Two dune fields have been found on the Magellan images: one on plains between Fortuna and Meskhent tessera massifs (Figure 14C) and another one on plains of the northern part of Lavinia Planitia [Greeley et al., 1997]. Both dune fields are in close association with large impact craters whose ejecta probably was the source of the debris involved in dune formation. The dunes are from 0.5 to 10 km long and a few hundred meters wide. Formation of dunes implies saltation of sand-sized particles, so the lack of observed dunes on Venus may indicate a deficit of debris of this size on the planet. The apparent lack of dunes could, however, be partially an observational effect. Analysis of radiophysical properties in several regions of Venus by Bondarenko et al. [2006] revealed a noticeable east-west asymmetry in the radar returns which was interpreted as possible dunes/ripples of meter to decameter size range.

**DISCUSSION**

The material units and structures described above are observed with minor variations over most of the planet, and are included on most of the geologic quadrangle and other maps of Venus [e.g., Bleamaster and Hansen, 2005; Brian et al., 2005; Bridges and McGill, 2002; Campbell and Campbell, 2002; Ivanov and Head, 2001, 2004a; McGill, 2000; Rosenberg and McGill, 2001]. Of particular interest in comparison with Earth are the belts of rift zones. These rifts differ from the Earth’s mid-oceanic rifts, which are the areas of the youngest volcanism bordered by progressively older volcanics. Although generally relatively young structures, Venus rifts cut through terrains and units of different ages, resembling in this, and in a number of other characteristics, terrestrial continental rifts rather than oceanic rifts. Structures that could be considered as analogs to terrestrial zones of collision and subduction are not observed.
Thus it is concluded that geodynamics on Venus does not operate in the plate-tectonics style, but rather in some other mode [e.g., Solomon et al., 1992; Hansen et al., 1997; Phillips, et al., 1997]. The lack of current and geologically recent plate tectonics is supported by the observation that despite the seemingly long evolution of many coronae, they do not show evidence for deformation and elongation with time suggesting that the “plate” on which they reside, has not been involved in lateral movement and intense deformation. Additional evidence against geologically recent plate tectonics on Venus is the seemingly random spatial distribution of impact craters mentioned above.

The surface geology of Venus is almost certainly dominated by basaltic volcanism forming globally extensive plains as well as abundant volcanic constructs. Except for a few unusual volcanoes with short, stubby, radar-bright flows [e.g., Moore et al., 1992], only the relatively rare steep-sided domes appear to be candidates for extrusion of compositionally more evolved viscous lavas [e.g., Pavri et al., 1992] although other suggestions on their nature have been published: low-eruption rate basaltic volcanoes [Fink and Griffith, 1998], increased content of dissolved water and difference in crystallinity [Bridges, 1995] or foamy basaltic lavas [Pavri et al., 1992]. However, knowledge that even a minor portion of the volcanism on Venus is not basaltic is very important for the understanding of the general petrology and geodynamical evolution of this planet, so future missions should plan measurements necessary to determine their mineralogy and petrology.

The rocks of the crust of Venus have suffered from compressional and extensional deformation. In local stratigraphic sequences and maybe on a global scale (see below) the involvement of the crustal materials in deformation generally decreased with time.

The characteristics of the most deformed and most ancient tessera terrain have yet to provide conclusive keys to the geodynamical origin of this most distinctive terrain, and several different models exist for the formation of tessera and the geodynamical evolution of the planet as a whole [e.g., Sukhanov, 1992; Bindschadler et al., 1992; Ivanov and Head, 1996; Hansen et al., 1997, 2000]. Future studies need to concentrate on this problem by acquiring significantly higher resolution imaging of the surface of Venus on a global or at least regional scale. This will provide a better understanding of the deformation history of tessera terrain. Further progress in geodynamic modeling and correlations of the geological information with geophysical data sets will also be very helpful.

Magellan images revealed somewhat less than 1000 impact craters on the surface of Venus. This led to a number of esti-

Figure 14. Examples of aeolian features: A – Depositional radar-dark wind streaks behind (downwind of) the tessera ridges protruding through the smooth plains, 0.9°S, 71.5°E. B – Erosional radar-bright wind streaks behind (downwind of) small volcanic shields, 22.3°N, 332.1°E. C - Part of the Fortuna-Meskhent dune field. Dune long axis orientation varies from E-W to NE-SW. Orientation of radar-bright wind streaks implies winds blowing towards the NW, 68°N, 90.5°E. D - Yardangs to the SE of the crater Mead, 9°N, 60°E.
mates of the mean surface age that are generally consistent with each other. The latest estimate suggests that the mean surface age of the planet is about 750 m.y., but any values between 300 m.y. and 1 b.y. cannot be excluded [McKinnon et al., 1997]. This means that we see the geological record of only the latest 10 to 20% of the history of Venus. Some material representing earlier time periods could be present as inclusions in tessera terrain. This implies that higher resolution imaging of tessera (meters to tens of meters per pixel), and analysis of its composition, should be high priority goals for future missions to Venus. Some progress in understanding the mineral composition of tesserae may be expected from night-time near-IR observations planned for the Venus Express mission.

Another message from the past of this planet is the deuterium anomaly, which suggests that Venus in early times was richer in water (e.g., Donahue and Pollack, 1983). There are models suggesting that Venus could have had an ocean for several hundred million years or possibly even longer [e.g., Kasting et al., 1984; Kasting, 1988; Grinspoon and Bullock, 2003]. If so, this could have affected the rheology and therefore the dynamics of the upper mantle and crust as well as magma formation and differentiation processes.

As noted by Solomon et al. [1992] in the early analysis of the Magellan data, in many different locations on Venus occur similar sequences of materials and structures. Basilevsky and Head [1995] mapped 36 1000 x 1000 km areas randomly distributed around the planet. Their results confirmed the observations of Solomon et al. [1992]. Extending that work, Basilevsky et al. [2000] and Ivanov and Head [2001] mapped the northern 25% of the planet as well as a continuous geotraverse circling the planet at ~30° N. latitude. The results were interpreted to support the existence of distinctive “phases” in the crustal evolution of Venus (Figure 15) during the time span represented by the currently exposed materials and structures [see summary in Basilevsky and Head, 2002b].

Following many of these early analyses, Guest and Stofan [1999 labeled this interpretation as a “directional” model and suggested the contrasting “non-directional” model, according to which “coronae, rifts, wrinkle ridges, small and large edifices, and large flow fields have each formed throughout the portion of Venus’ history revealed by presently exposed rock units” (their page 55). These ideas are currently being debated.

One of the findings of earlier works [e.g., Basilevsky and Head, 1998, 2000; Ivanov and Head, 2001] is that regional plains occupy a central position of the regional and global stratigraphic columns and that these plains appear to have a broadly similar age. Variations in the radar backscatter of the regional plains are common, implying that these plains consist of many different flows from several different possible sources [e.g., Stofan et al., 2005]. Nevertheless, the regional plains as a whole are characterized by an impact crater distribution that was found to be not distinguishable from random [e.g., Schaber et al., 1992; Phillips et al., 1992]. More recently, Hauck et al. [1998], concluded that although the hypothesis of complete spatial randomness of the crater distribution cannot be rejected, the modeling suggests a possible spread in the ages of plains that might exceed half the mean global surface age. Unfortunately, plains used by Hauck et al. included materials that, based on geologic evidence, are younger or older than regional plains, and thus their work does not constrain the age of regional plains [see for details Basilevsky and Head, 2006].
Can widespread units such as the regional plains thought to be globally equivalent stratigraphic units by some [e.g., Basilevsky and Head, 1996; Ivanov and Head, 2001] be correlated using the existing crater data? Campbell et al. [1999] argued that determining the relative ages of separate areas within the plains can not be statistically robust because of the small number of craters available. Thus, using crater statistics alone, Campbell et al. [1999] would conclude that the relative ages of separated plains units cannot be confidently established.

A number of studies have been undertaken to determine the time sequences of different material units and structures, for example, on tessera terrain [e.g., Ivanov and Head, 1996; Hansen et al., 1997; Gilmore and Head, 2000; Hansen et al., 2000], or on the relative ages of regional plains and shield plains [e.g., Basilevsky and Head, 1996; Hauck et al., 1998; Campbell, 1999; Addington, 2000; Ivanov and Head, 2001, 2004b; McGill, 1993, 2004; Hansen, 2005]. Although not resulted in general consensus, these studies have led to the descriptions of many important details, and also to greater clarity of the different researchers’ positions.

We would like to conclude the discussion by a comparison with greenstone belts on Earth [e.g., De Witt and Ashwal, 1997]. These belts are common in Archean and earliest Proterozoic terrains, but rare or absent in younger terrains. Thus at the largest time scale, the history of greenstone belts is directional. However, based on radiometric dating, greenstone belt formation within the Archean and earliest Proterozoic clearly occurred in different places at different times. Perhaps we can think of some aspects of Venus crustal history in the same way: characterized by a prominent trend for the larger time intervals, and by repetitive components at shorter time intervals.

**KEY QUESTIONS TO BE RESOLVED IN FUTURE STUDIES**

As evident from the above description and discussion, analysis of the results from many missions and from laboratory and theoretical studies has led to significant progress in understanding major issues of Venus geology. However, many important questions still wait to be resolved in future studies. Below is a short list of some of them:

- What was the mechanism of tessera formation (deformation resulted from upwelling or downwelling) and how long was the tessera-forming phase?
- How did the folded mountain ranges surrounding Lakshmi Planum form?
- What caused the deformation typical of densely fractured plains, ridge belts and wrinkle ridges; in particular, how can we explain the stresses necessary to form areally extensive coherent arrays of wrinkle ridges?
- Is Venus still volcanically and tectonically active?
- Are coronae manifestations of mantle plumes? Are some of them still active?
- What is the origin of layered rocks seen in the Venera panoramas?

Although the Venus Express mission is designed mostly to gain data for atmospheric and plasma science, it may shed some light on the compositions of tesserae and mountain belts. This could be possible if measuring the near infrared emissivity from these terrains is successful. Progress in atmospheric dynamics and chemical composition may lead to better understanding of the surface geological processes. But serious progress in resolving the above mentioned questions demands new missions, including orbiter(s), balloons, landers and sample return.

An increase of surface imaging resolution is needed to see more detail (meters to tens of meters per pixel) and thus to better understand the nature and age relations of different material units and structures, and to link the Magellan global imagery with in-situ lander observations. Higher resolution SAR radar imagery, as well as images taken by future landers on their descent or by balloons, may be the preferred approach.

New landings are needed to obtain geochemical analyses on the Venus surface with the capability to broaden the range of determined elements (and possibly detect isotopes) with higher accuracy than in the past. Landing sites also should target terrains not analyzed in the past (tesserae, mountain belts, steep-sided domes). Long-term observations on the surface involving seismic measurements are crucial for understanding the internal structure and the level of present endogenous activity of Venus. For more distant perspective we should also plan sample return missions to Venus that could lead to significant progress in understanding petrogenesis on that planet and that could determine material ages now only estimated using impact crater counts.

**CONCLUSIONS**

The above descriptions and discussion show that although many important problems of Venus geology are still not
resolved (for example, scarcity of impact craters on the planet surface complicates integration of the observed sequences of material and structural units into any single stratigraphic model) it is already clear that among other terrestrial planets Venus holds a unique place. Its relatively young surface, formed by a number of volcanic and tectonic processes, certainly distinguishes it from the smaller bodies: the Moon, Mercury and Mars. This is obviously the result of the net energy budget: in contrast to Venus the small bodies reached a stage of thick and rigid lithosphere relatively early in their histories [e.g., Toksoz et al., 1978; Solomon and Head, 1982; Basilevsky and Kreslavsky, 1992; Basilevsky, 1994]. More enigmatic is an obvious difference between the geologies of Venus and Earth. Although if one ignores the exogenic processes and resulted materials, both planets show abundant volcanism and tectonism. However, they are different in geodynamic styles. Venus lacks evidence of active plate tectonics in the morphologically surviving part of its history (the last 1 b.y. or less). This may be due to the lack of water on its surface, which is considered by some researchers as implying very dry crust and upper lithosphere. This in turn may be responsible for high stiffness of the planet’s interior precluding plate tectonics. The key difference in geochemistry is in abundance on Earth of granitic materials and lack of evidence of its presence (at least in significant amount) on Venus. This may also be due to the lack of plate tectonics (and water) on Venus because the granitic crust of Earth is considered to be a result of the plate-tectonic recycling with important role of water in the fractional melting and crystallization differentiation. All this shows that the principles controlling the key geologic processes and geodynamic styles on the planetary bodies are still not fully understood.

REFERENCES


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