The Geology of Venus

by George E. McGill

Despite similarity in bulk properties to Earth, surface and crustal conditions on Venus imply distinct exogenic and tectonic processes. Wind transportation is probably the dominant geomorphic agent on Venus, but all surface processes except impact are severely constrained by the extreme dryness. High crustal and lithospheric temperatures lead to models of a buoyant lithosphere. The strongly unimodal topography and absence of a global system of trenches, ridges, and mountain chains indicate that the tectonic style of Venus differs from that of modern Earth. However, some topographic features suggest the existence of incipient divergent boundaries, and gravity data and radiogenic argon abundance imply that Venus is a tectonically active planet, with certain characteristics possibly in common with the Archaean Earth.

General Features: A Contrast with the Earth

Of all the planets and moons in our solar system, Venus is of greatest interest to geologists because it is closest to the Earth in size and bulk properties (Table 1). However, because clouds perpetually shroud the planet, conventional optical telescopes and television cameras carried by spacecraft are of no use for studying its surface. Our present knowledge of the venusian surface derives almost entirely from three sources: U.S. and Soviet Earth-based radar, Soviet Venera missions and the U.S. Pioneer Venus mission.

Data of geological significance include radar images, radar altimetry, chemical and physical properties of the rocks, images of the surface close to some of the Venera landers, atmospheric composition and temperature, wind speeds and gravity anomalies. Also important are observations on small-scale surface properties that influence the nature of the radar signal reflected from the surface area illuminated by the transmitted radar beam. These include dielectric properties, surface roughness and average (root mean square = rms) surface slope angles.

Property	Earth	Venus	Ratio (Earth=1)
Mass (kg)	5.976×10^{24}	4.871×10^{24}	.815
Equatorial radius (km)	6378	6052	.949
Mean density (g/cm ³)	5.52	5.24	.949
Equatorial surface gravity (m/s)	9.78	8.87	.907
Sidereal rotation period (earth days)	.9973	243.01 (retrograde)	
Solar day (earth days)	1	116.75	
Sidereal revolution period (earth days)	365.256	224.701	
Surface atmospheric P (bars)	1	95	
Surface T (°C)	22	465	

TABLE 1: Comparison of Earth and Venus.

The uncorrected mean density of Venus is 4.9% less than that of Earth (Table 1). Part of this difference is due to the smaller mass of Venus, but if it possessed a structure and bulk composition exactly like that of the Earth, Venus should

have a density of 5.34 g/cm³, or 1.9% greater than that observed (BVSP, 1981, p. 682). A number of models have been proposed to account for this residual density deficiency, but the most likely ones require the composition of the venusian mantle to be very similar to that of the Earth's. The most significant of the probable differences is a somewhat higher MgO/(MgO + FeO) ratio in the mantle of Venus. Consequently, geophysical models of the thermal structure and tectonic style of Venus generally start by assuming an approximately Earth-like mantle, one that is convecting and that is very similar in composition, characterized by an "average" temperature equal to or slightly higher than that for the Earth (Phillips and Malin, in Hunten et al., 1983).

In contrast, the surface environment is very different from that of the Earth (Table 1). The high atmospheric pressure, high surface temperature, and lack of H₂O suggest that surface processes should not be the same as on Earth, or at least that the same processes should not be dominant. In addition, the latter two features imply a hot, dry crust and a hot lithosphere, with very interesting consequences for tectonic style. It is this combination of similar mantles and dissimilar surfaces that lends special interest to geological comparisons between Earth and Venus.

There are no data of sufficient resolution to identify individual rock units, and thus to infer the underlying structure of the topography, or landforms diagnostic of potentially important surface processes. Nevertheless, some general constraints can be placed on the geological processes and tectonic history of Venus from the data in hand.

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	$1.82^{+1.65}_{-0.85}$
9	0.60 ± 0.16	3.65 ± 0.42	0.47 ± 0.08	$0.78^{+0.47}_{-0.27}$
10	0.46 ± 0.26	0.70 ± 0.34	0.30 ± 0.16	$0.65^{+1.65}_{-0.46}$

TABLE 2: Venera Measurements of Uranium, Thorium, and Potassium Abundances (Surkov, 1977).

Surface Composition and Physical Processes

The Soviet Venera 8, 9, 10, 13, and 14 landers provided valuable data on the composition of surface materials. Veneras 8, 9, and 10 determined abundances of K, U, and Th (Table 2) by means of gamma-ray spectrometry, and Veneras 13 and 14 carried X-ray fluorescence spectrometers that determined major-element abundances (Table 3) in small cores drilled from exposed rock. The compositions determined at all five sites are distinct from primitive, undifferentiated chondritic material (Fig. 1). They are, however, comparable to igneous rocks found on Earth, as is to be expected if Venus has a mantle compositionally similar to that of the Earth and if normal differentiation processes were involved in crustal genesis.

The Venera 9, 10, and 14 samples appear to be similar to tholeiitic basalts on Earth (Surkov, 1977; Surkov et al., 1983). The association of high K with a basaltic composition at the Venera 13 site suggests that the K-rich sample from Venera 8 may also be basaltic (Surkov et al., 1983). All except Venera 8 are near the Beta Regio-Phoebe Regio area (Fig. 2), inferred to contain large basaltic shield volcanoes (Masursky et al., 1980) or to be a zone of continental rifting with associated basaltic volcanism (McGill et al., 1981). Consequently, it is very likely that the Venera samples are not representative of the entire planet.

Veneras 9, 10, 13, and 14 also returned images of the surface near the landers (Florensky and others, in Hunten et al., 1983). These show a mostly rocky surface, with a dark, apparently fine-grained regolith-like material present in amounts varying from site to site (Fig. 3). Much of the rock appears to be layered, and weathering and disruption of the bedrock are also evident. Measured rock density at the Venera 10 site (Surkov et al., 1976) of 2.8 g/cm³ suggests igneous rock. A pyroclastic origin is much more probable for the rocks at the Venera 14 site, where the chemical composition is consistent with an igneous origin, the layering is thin and well defined and the rocks have a low density (~ 1.5 g/cm³) and an apparent porosity of about 50% (Florensky et al., 1983).

Figure 1: Potassium abundances and K/U ratios for selected planets and meteorites. From Taylor (1982).

Earth-based and spacecraft radar provide useful information on surface roughness at about the scale of the radar wavelength (cm-dm), rms slopes at a scale ≥ 10 times the radar wavelength, and the dielectric properties of surface materials (calculated from the Fresnel reflection coefficient). Krotikov (1962) determined an empirical relationship between dielectric constant and density of dry, nonconducting, porous materials such as are found on Venus and the Moon. If the original rock composition is known, the dielectric constant may also be used to infer the porosity from the Rayleigh mixing formula, which relates the densities and dielectric constants of coherent solids and their powders. The results from both Earth-based and spacecraft radar indicate that most of the surface material of Venus has a density consistent with slightly weathered igneous rock (Kuz'min and Marov, 1974; Pettengill et al., 1982). The Fresnel reflectivity characteristic of most of the surface is 0.12 ± 0.03 , which corresponds to a density for surface materials of 2.1 ± 0.4 g/cm³ (Pettengill, *ibid*).

The Rayleigh mixing formula indicates that rock with the mean dielectric constant for the surface of Venus could be weathered basalt with 20% porosity or "granite" with 5% porosity (McGill and others, in Hunten et al., 1983). Only a very small total area has Fresnel reflectivities indicating surface material with a density low enough to be consistent

with a thick, high-porosity surface layer (Pettengill, *ibid*). Consequently, Venus cannot be covered by a thick, porous regolith as is the Moon.

Some of the Venera landers evidently raised dust from the surface (Ekonomov et al., 1980), and the Venera 9, 10, and 13 images of the surface (Fig. 3) certainly suggest the presence of material that looks like a regolith. However, radar results indicate that this is either restricted in occurrence or very thin (of the order of a few centimeters thick at most). It is possible, of course, that much of the surface consists of cemented regolith or sediment, because the radar is primarily sensitive to the bulk density. If so, the Venera chemical analyses would seem to require that the processes of weathering, transportation, deposition and lithification that produced the cemented regolith or sediment involved so little sorting that the resulting rock is compositionally indistinguishable from the parent igneous rock. This seems to strain credulity somewhat, but if it is true then the almost total lack of chemical sorting would provide a severe constraint on venusian surface processes.

A few small areas on Venus are characterized by Fresnel reflectivity coefficients that are much too high to be due simply to nonconducting rocks with very low porosity. Most of these areas are topographically high, and some coincide with features suspected of being young volcanoes. The most likely explanation is that exposed bedrock in these regions contains a significant percentage of small conducting mineral grains, such as sulphides (Pettengill et al., 1982).

Globally, Venus has average slope angles that are low relative to Mars and the Moon, as had been known from earlier Earth-based observations (Evans, 1969). The Pioneer Venus observations indicate that variations from the globally characteristic average slope angle of $\sim 4^\circ$ are correlated with topography; low areas tend to have low rms slopes, whereas high areas and areas of relatively steep topographic slope tend to have high rms slopes (Pettengill et al., 1980).

Oxide	Weight Percent	
	Venera 13	Venera 14
SiO ₂	45 $\pm$ 3	49 $\pm$ 4
TiO ₂	1.6 $\pm$ 0.4	1.2 $\pm$ 0.4
Al	16 $\pm$ 3	18 $\pm$ 3
FeO	9 $\pm$ 2	9 $\pm$ 2
MgO	11 $\pm$ 6	8 $\pm$ 3
CaO	7.0 $\pm$ 1.0	10 $\pm$ 1.2
K ₂ O	4.0 $\pm$ 0.6	0.2 $\pm$ 0.1
MnO	0.2 $\pm$ 0.1	0.16 $\pm$ 0.08

TABLE 3: Preliminary Results of X-Ray Fluorescence Analyses by Veneras 13 and 14 (modified from Surkov et al., 1983)

Earth-based radar observations at intermediate values of the incidence angle (~ 20 - 60°) and Pioneer Venus side-looking radar images are sensitive to surface roughness at about the scale of the radar wavelength. Again, there is a correlation with topography; low areas tend to be smooth, high areas and steep slopes rough (Campbell and Burns, 1980; Pettengill, *ibid*). Thus, Venus exhibits excellent global correlation of topography, rms slope, and wavelength-scale roughness. Most of the planet is characterized by intermediate values of all three parameters, high areas and slopes are rough, and low areas are very smooth. Exceptions to this correlation make up a very small fraction of the known surface.

Surface Processes

Little direct evidence exists to support or refute the action of any specific surface process. Discussions of this topic are

mainly limited to establishing constraints and speculating on the probable rate of surface modification. The key environmental parameters are the total lack of liquid water, the atmospheric composition, and the high atmospheric temperature and pressure (Table 1). Because the total relief of the Venus topography exceeds 13 km (Pettengill *et al.*, 1980), the surface atmospheric temperature and pressure differ by at least 100°C and 6 MPa (60 bars) between the highest and lowest points on the planet. This is an important range of pressure and temperature for probable weathering processes.

Theoretical considerations suggest that chemical weathering of common igneous rocks is to be expected on Venus (Mueller and Saxena, 1977; Lewis, 1970; Barsukov *et al.*, 1980). Much less certain is whether or not the high surface temperature leads to reaction rates fast enough to permit weathering reactions to buffer the atmospheric composition. The large range in pressure and temperature with elevation suggests that there may be geochemical cycles involving the consump-

andalusite, dolomite and either sulphides or sulphates (McGill and others, in Hunten *et al.*, 1983). Additional reactions at lower elevations could produce calcite and tremolite (Nozette and Lewis, 1982). The mineralogy will, of course, depend on the rock types being weathered, as well as on the reaction kinetics and the exact composition of the lower atmosphere.

Modification of the surface to a geologically significant extent requires not only processes of erosion and transportation capable of rapid redistribution of unconsolidated material, but also efficient weathering to disaggregate solid rock fast enough to keep pace with these processes. The absence of water on Venus is clearly the dominant factor in evaluating rates of all exogenic processes, except impact cratering, because the great majority of weathering, erosion and transportation processes on Earth require the presence of either liquid water on the surface or significant H₂O vapour in the atmosphere.

Figure 2: Locations of the Venera landing sites. Mercator projection of topography shows regions >1 km below median elevation in heavy stipple, median $\pm$ 1 km in light stipple, and >1 km above median blank.

tion of atmospheric CO₂ in elevated regions (relatively low temperature and pressure), and transport of the weathering products to low elevations where other reactions return the CO₂ to the atmosphere (Nozette and Lewis, 1982).

The exact reactions involved are difficult to predict because the lower atmosphere abundances of key minor constituents and the kinetics of most of the proposed reactions are not known (von Zahn and others, in Hunten *et al.*, 1983). In general, however, the most likely chemical weathering reactions should produce a regolith at high elevations consisting of minerals such as magnesite, enstatite, quartz, tremolite,

The only readily envisaged process for mechanical weathering on Venus is related to the generation of spalling stresses in the surfaces of exposed rocks due to volume changes accompanying chemical weathering. Although there are no data whatever to permit an estimation of the effectiveness of this process, intuition suggests that it is very slow. Indeed the slowness of mechanical weathering may well be the main control on the overall rate of surface modification, which is certainly much less than on Earth.

Only two transportation processes seem possible: mass wasting and aeolian transport. The first can be only of local importance, so if there is any significant volume of material transported for long distances on the surface of Venus it must

be carried by the wind. Veneras 9 and 10 carried rotary anemometers that measured wind speeds 1 m above the surface in the range 0.4 to 1.3 m/s (Keldysh, 1977). Acoustic sensors on Veneras 13 and 14 were used to estimate near-surface wind speeds of 0.3 to 0.6 m/s on the basis of comparisons with wind tunnel simulations (Moroz, in Hunten *et al.*, 1983). Counselman and others (1980) used differential long-baseline interferometry to track three-dimensional velocity vectors of the Pioneer Venus atmospheric probes, with the inference that near-surface wind velocities average about 1 m/s. These wind data imply surface friction speeds of the order of several cm/s, which are more than adequate to entrain and transport silt- and sand-sized particles (Fig. 4; Iversen *et al.*, 1976).

Topography and Tectonics

In sharp contrast with the bimodal distribution of elevations on Earth, the topography of Venus is strongly unimodal (Fig. 5); the median radius is 6051.6 km, and the modal radius is 6051.4 km (McGill and others, in Hunten *et al.*, 1983). The total relief measured by the Pioneer Venus radar altimeter over 93% of the surface of Venus is about 13.5 km (Pettengill *et al.*, 1980). However, because the surface area included in each altitude measurement varies from 7 x 23 km where the spacecraft is closest to the planet ($\sim 17^\circ$ N. Lat.) to more than 100 km across at high latitudes, and because altitude measurements are generally some tens of kilometers apart, the Pioneer Venus data almost certainly understate the true

Figure 3: Panoramic images of the Venera 13 (a) and Venera 14 (b) landing sites. The camera is 0.9 m above the surface, and scans about an axis inclined 50° from the vertical. The trellis girder left of center is 60 cm long, and the colour test band to the right is 9 cm wide (Moroz, 1983).

In general, aeolian mass flux due to saltation is proportional to the cube of the surface friction speed and to the ratio between atmospheric density and the acceleration of gravity (Bagnold, 1941). In contrast to the situation for Earth, the much greater atmospheric density and the lower gravity of Venus indicate potentially higher mass fluxes, but if the measured wind speeds are characteristic, then the lower surface friction speeds on Venus would more than counteract the density and gravity differences. The total sediment movement by wind on Venus is thus unlikely to be significantly greater than that on Earth, and may well be less. Consequently, even if the Venusian weathering processes did provide abundant sand-size and smaller particles, there seems to be no process capable of moving them at rates even remotely comparable to the rate of transport by water on Earth. And as discussed earlier, the global radar data support this conclusion by indicating the absence of a thick, widespread, unconsolidated surface layer.

relief. This means that the total surface relief of Venus is very similar to that of Earth, but the percentage of terrain with elevations near the median and mode is much higher on Venus than on Earth.

Thus, 60% of the known surface of Venus lies within 500 m of the modal radius, indicating globally dominant "rolling plains" with elevations close to this radius (Masursky *et al.*, 1980). There are only a few small, generally irregular low areas that are 1-2 km lower than the median elevation, and only two elevated regions of "continental" dimensions; Ishtar Terra, about the size of Australia, and Aphrodite Terra, close to Africa in size (Fig. 2). These rise to as much as 10.5 km above the median elevation.

There is a close correlation between gravity and topography on Venus, with positive anomalies coinciding areally with topographically high areas, and negative anomalies with topographically low areas (Sjogren *et al.*, 1980; Phillips *et al.*,

Figure 4: Threshold friction speed vs. particle diameter under venusian conditions for particle densities σ of 2 and 3.5 g/cm³.

1981). Anomalies of similar wavelength on Earth do not correlate with topography, and are generally believed to be related to dynamically maintained density inhomogeneities in the upper mantle. Calculated depths of compensation for large positive anomalies on Venus (Reasenberg et al., 1982) indicate that they, too, are related to dynamically maintained density inhomogeneities in the mantle. By inference, therefore, the associated venusian topography is also related to underlying mantle density anomalies.

No global system of ridges, transforms, mountain chains, and trenches comparable to that on Earth can be seen in the topography of Venus (Fig. 6). This observation and the unimodal spectrum of elevations suggest that the topography of Venus is not due to an Earth-like plate tectonics (Masursky et al., 1980; Kaula and Phillips, 1981; Phillips et al., 1981; McGill and others, in Hunten et al., 1983). Thus the most straightforward interpretation of the observations is that the tectonic styles of Venus and Earth are different.

The bimodal distribution of elevations on Earth depends, of course, on the operation of plate tectonics, on the existence of significant abundances of two kinds of crust (sialic and simatic), and on the freeboard effects of the oceans. Although the Venera 8 abundances of K, U, and Th can be

interpreted to imply sialic crust, the data are open to other interpretations (Surkov et al., 1983) and furthermore, the existence locally of some sial does not necessarily require its presence globally. The anomalously high deuterium/hydrogen ratio in the atmosphere of Venus indicates abundant H₂O early in the history of Venus (Donahue et al., 1982), suggesting that the differentiation of sial at that time is a reasonable assumption. However, there is no unequivocal chemical evidence to prove the existence of sialic crust.

In the absence of oceans on Venus, the erosional base level will be the minimum elevation rather than sea level. But the dominant processes of lateral transport on Venus are aeolian, so that an erosional base level may have little significance. Furthermore, the expected rates of lateral transport are far less than on Earth. Thus it would be reasonable to interpret the unimodal elevations of Venus as evidence against plate tectonics if we had independent evidence for abundant sial. Unfortunately, such evidence does not now exist.

Figure 5: Hypsometric histograms of Earth (left) and Venus (right) in 1 km elevation intervals. Elevation scale at left is relative to sea level on Earth; the histograms are aligned at their median elevations.

The absence of a global topographic system similar to that on Earth certainly does not favour venusian plate tectonics, but whether or not it constitutes positive evidence against plate tectonics is controversial. For example, Arvidson and Davies (1981) have shown that the Pioneer Venus altimetry has sufficient resolution to see the topographic evidence for plate tectonics if it were like that on Earth, corrected only for the higher lithospheric temperature and absence of oceans on Venus. But should plate tectonics on a waterless planet with a hot lithosphere produce a global topographic system like that of Earth? We do not know, but there are a number of arguments suggesting that it would not (Solomon and Head, 1982). In fact, modern Venus may be more like the Archaean than the modern Earth, and it is abundantly clear that we do not yet understand the tectonic style of Archaean Earth.

The tectonic style of a planet depends on the dominant processes involved in transferring heat through the lithosphere. Both Venus and Earth appear to have convecting mantles (Schubert et al., 1969) of nearly the same composition and temperature. Furthermore, the abundance of radiogenic ⁴⁰Ar in the atmosphere of Venus is less than its abundance in the Earth's atmosphere only by a factor of 3 (Hoffman et al., 1980). Very little ⁴⁰Ar existed when the

Figure 6: Mercator projection of Venus topography represented in continuous gray tones. White areas are high, dark areas low.

Figure 7: Topographic map of a portion of Aphrodite Terra characterized by a low, narrow ridge that connects more elevated portions. Contour interval 0.5 km, with some lines feathered on steep slopes; datum is median radius.

planet underwent any primordial differentiation that may have occurred; instead, it has been continuously produced by the decay of ^{40}K in the interior of the planet. The proportion of this ^{40}Ar reaching the atmosphere depends on proportion of this ^{40}Ar reaching the atmosphere depends on the vigour of tectonic and volcanic processes that transport the ^{40}Ar to or close to the surface. Because Earth and Venus are believed to be compositionally very similar, the comparable atmospheric ^{40}Ar abundances imply comparable overall tectonic-volcanic activity when averaged over geological time. Hence, any differences in tectonic style must be due primarily to differences in the lithosphere and crust.

On Earth, about 60% of the modern heat flow through the lithosphere is directly related to plate creation at divergent boundaries, and another 5% to processes at convergent boundaries (Sclater *et al.*, 1980). If Venus does not have a global plate-tectonic system, then a much higher percentage of its internal heat must pass through the lithosphere by conduction and volcanism than is the case for modern Earth. This has led to the proposal that the tectonic style of Venus is dominated by hot spots (Phillips and Malin, in Hunten *et al.*, 1983), comparable to the hot spots known on Earth, but more abundant and perhaps larger.

The only alternative so far proposed (Solomon and Head, 1982) is

a fast form of small-scale plate tectonics similar to the models favoured by some for Archaean Earth. However, any form of plate tectonics proposed for Venus poses severe geophysical problems because the lithosphere is likely to be positively buoyant everywhere (Anderson, 1981; Phillips and Malin, *ibid*). This is so partly because it is hot, but also because the lower mass of Venus and the higher temperature of its crust and upper mantle relative to that of Earth will suppress the basalt-eclogite phase transition (Anderson, *ibid*). Moreover, a hot lithosphere is likely to be thin and thus to have a higher crust/mantle ratio than a thicker lithosphere. If the lithosphere is positively buoyant everywhere, there can be no slab pull, and thus the most popular driving force for Earth plate tectonics cannot exist on Venus.

The topography of Venus contains some interesting clues to the tectonic style. Schaber (1982) mapped three narrow zones, 6000, 14000 and 21000 km long, that are slightly higher than their surroundings, relatively rough at centimeter scale and characterized by relatively high rms slopes. Included within these zones are some topographically higher regions, such as Aphrodite Terra, Beta Regio and Phoebe Regio (Fig. 2), and also several large rift-like troughs. The 6000 km long zone from Beta Regio to Phoebe Regio has been compared to the East African continental dome and rift system (McGill *et al.*, 1981).

Figure 8: Topographic map of western Ishtar Terra showing a large plateau (Lakshmi Planum). Contour interval as in Figure 7.

Figure 9: Topographic map (A) of Maxwell Montes, a large massif in Ishtar Terra. The Earth-based radar image (B) resolves the massif into many light and dark bands, and indicates the presence of a large crater (caldera?). Image courtesy of D.B. Campbell. Contour interval as in Figure 7.

Other parts of the system are more complex, with major rifts and flanking linear mountain systems, or with many irregular closed depressions interspersed with irregular elevated areas (Fig. 7). The coincidence of elevated topography with either rifts or irregular depressions suggests that these are zones of thin lithosphere, higher than average heat flow, enhanced volcanism and perhaps minor lateral spreading, comparable to continental rifts or to hot spots on Earth. Their concentration along large-scale linear zones further suggests that the latter may be incipient divergent boundaries. If significant subduction were possible elsewhere, then significant divergence should develop along these zones.

In contrast, Ishtar Terra has many characteristics of a continent (Phillips and Malin, in Hunten and others, 1983). Much of Ishtar Terra is a large plateau, Lakshmi Planum, that rises 3-4 km above the adjacent rolling plains, and that is bordered on the south, west and north by linear or arcuate elevated terrain (Fig. 8), and on the east by Maxwell Montes, a large massif that includes the highest measured elevation on Venus (Fig. 9). The linear mountain belts to the west and north of Lakshmi Planum, Akna and Freyja Montes (Fig. 8)

are resolved by Earth-based radar into a number of alternating bright and dark bands. These parallel the long axes of the belts and have characteristic widths of 10-20 km (Campbell et al., 1983), comparable to the dimensions of fault or fold-belt mountain chains on Earth. It is tempting to argue therefore that the topographic characteristics of Ishtar Terra favour plate tectonics because significant convergent motion is suggested. But this contradicts both the geophysical expectations and the most reasonable interpretation for the absence of the global system of topographic features diagnostic of plate tectonics.

Ishtar Terra could be a relic of a plate tectonic regime active in the early history of Venus (Phillips et al., 1981), but the high venusian crustal temperature suggests that major topographic features are likely to be young, and that distinctive topographic forms such as those visible in Figures 8 and 9 would subside in times that are short relative to the age of Venus (Weertman, 1979; Solomon and Head, 1982). The only compromise solution would seem to be that heat flow and hence crustal temperatures are highly variable, and that Ishtar Terra is a region of thick, old crust with low heat flow (Phillips and Malin, in Hunten and others, 1983). This solution is similar to some that have been proposed to reconcile evidence for thick sialic crust on Archaean Earth with the expectation of higher than modern heat flow, based on the backward extrapolation of total radiogenic heat.

Crater-like shapes visible on Earth-based radar images prompted several efforts to date the crustal surface of a portion of Venus by comparing diameter/frequency plots for venusian craters with similar plots for the Moon. Although some of the smallest of these shapes do resemble impact craters, based on comparisons with radar images of lunar craters (Goldstein et al., 1976; Campbell and Burns, 1980), improved Earth-based imagery and the Pioneer Venus altimetry suggest that most of the larger forms (up to hundreds of kilometers in diameter) are probably not due to impact. Consequently, all attempts to date the surface of Venus with these features are at best premature.

The problem of the origin of the crater-like features remains open. The topographic relief of ancient large craters and basins on Venus will have been lost by viscous relaxation long ago (Solomon et al., 1982). Most of the roughly circular shapes seen on Earth-based radar images do not coincide with topographic depressions resolvable with Pioneer Venus altimetry. But the Earth-based radar images record areal variations in centimeter-scale surface roughness, and areas underlain by rock that has been intensely shattered by meteorite impact could easily appear as anomalously rough on a radar image. Such small-scale roughness will not disappear as a result of viscous relaxation, so we cannot rule out the possibility that some of the enigmatic shapes on radar images are relics of large ancient craters and basins.

It is significant to note that if some of these roughly circular patterns are relics of large craters and basins surviving from the period of early bombardment (>3.9 Ga ago), then the rate of surface modification on Venus must be very slow indeed. Alternatively, these patterns could represent volcano-tectonic depressions of much more recent origin. Because most of them are irregularly shaped in plan, this is the more likely hypothesis.

In summary, the evidence so far suggests that Venus is tectonically almost as active as Earth, but with a different style from the plate tectonics characteristic of modern Earth. What remains controversial is whether the tectonic style involves an essentially single-plate lithosphere dominated by conduction and volcanism at hot spots and rift zones, or whether it is related to fast spreading along divergent boundaries that define a lithosphere broken into many small plates. This problem is very similar to that faced by students of Archaean Earth tectonics.

Directions for Future Research

Even though we have made great strides during the past decade in our efforts to understand the geology of Venus, the major questions remain unanswered. Better resolution altimetry and imagery are clearly needed, as are more chemical analyses of surface rocks and of the lower atmosphere. Imaging by the Venus Radar Mapper (VRM) mission planned by NASA will provide near-global coverage at a resolution comparable to that of the Mariner 9 vidicon images of Mars (Morrison and Hinniers, 1983). It proved possible to infer the origin of many major landforms on Mars, and to outline the geologic history of the planet with the Mariner 9 data. It should be possible to attain comparable objectives with VRM data: ancient basins and large craters, volcanic landforms, patterns indicative of folding or faulting, distribution and relative ages of surface units, and large landforms suggesting the operation of important surface processes should all be resolvable if they are present.

Additional clues to surface processes may well be discovered, for the Mariner 9 images were able to resolve features such as dune fields, yardangs and valley networks. We also anticipate a continuing program of Venera missions providing essential data on surface properties and composition, providing additional topographic data, and, we hope, resolving some

of the critical remaining uncertainties concerning the abundances of important minor atmospheric constituents. All these data, along with more and better Earth-based radar images, should permit development of secure models for the geology and tectonic evolution of Venus, and perhaps even clues to the early tectonic and surface evolution of the Earth, as suggested in the following article.

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