REMOTE SENSING OF SURFACE PROCESSES

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Surface weathering processes on Venus occur at rates several orders of magnitude slower than those on Earth. This is due in large part to the absence of water, minimal diurnal temperature changes, and lack of strong winds near the surface. Erosion rates are thus similar to those on the Moon, but the dense atmosphere and relatively young age of the surface have prevented the formation of a thick regolith. Much of the terrain on Venus is comprised of smooth bedrock and closely packed fragmental debris, of basaltic composition. Mechanical and chemical erosion reduce the meter-scale roughness of rocky surfaces over time scales of millions of years, but a major source of fine-grained material which can be moved by the wind is likely impact crater formation. Young craters have associated parabolic haloes of fine material, which are dispersed on time scales of a few tens of millions of years. The close association of the few identified dune fields with impact craters further argues for these events as the primary source of fine sediment and transient high winds. Enhanced radar backscatter and low emissivity in the highlands may be caused by loading of rocks with conductive or ferroelectric minerals which are stable only at higher elevations, or by cold trapping of such materials transported by the atmosphere. Questions as to the specific mineralogy of the highlands, the distribution of sediments, and the role of chemical weathering at the surface remain to be addressed by future missions.

I. INTRODUCTION

Our knowledge of the surface properties of Venus comes from observations by Venera, Vega, and Pioneer Venus landers, radar maps of the planet produced by Pioneer Venus Orbiter, Venera 15 and 16, and Magellan, and from Earth-based radar mapping by the Arecibo and Goldstone antennas. Geochemical data from the landers imply a predominantly basaltic composition for the surface, with one site indicating possibly more alkalic rock (Surkov 1983; Basilevksy et al. 1992; Weitz and Basilevsky 1993). Radar images reveal a surface dominated by relatively smooth plains, interspersed with gently sloping shield volcanoes and upland plateaus of highly deformed terrain. The bedrock geology is overprinted by several processes: (1) comminution of surface rocks by chemical or mechanical (including impact) weathering; (2) redistribution of fine-grained soil by mass movements or winds (due either to global circulation or impact cratering); and (3) "highlands" weathering and/or modification related to surface-atmosphere interactions. We use the term "soil" here to indicate layers of debris with variable, though small, grain sizes. Impact cratering in particular produces fine material, scours large areas of the surface, overturns rock layers, and creates transient high winds. Each of these surface processes is strongly affected by the unique environment in terms of the high surface and atmospheric temperature, the high atmospheric pressure, the lack of diurnal temperature excursions, the trace element chemistry of the atmosphere, and the lack of water (cf., McGill et al. [1983] for a pre-Magellan review of surface processes on Venus).

In this chapter we first provide an overview of surface processes which operate in the Venus lowlands, and the remote sensing methods used to characterize them. We then focus on the unusual microwave properties of the Venus highlands and models which may explain these observations. We conclude with a brief summary of important issues which remain to be addressed by future Earth-based and spacecraft measurements.

II. OVERVIEW OF SURFACE PROCESSES OPERATING IN THE LOWLANDS

A. Mechanical and Chemical Weathering

The mineralogy of the surface of Venus has never been directly measured, because the lander experiments carried by the Venera and Vega spacecraft permitted derivation of only bulk elemental abundances. Interpretation of these data varies, but some form of basaltic composition is generally agreed to fit the majority of the surface measurements. The initial appearance of Venus from Magellan radar images is of a relatively fresh surface; impact craters have sharply defined rims, wrinkle ridges contrast strongly with the plains, and even very steep slopes do not exhibit large talus deposits. The subdued structures of older lunar or Martian craters and highlands are not evident.

The relative youth of the surface is confirmed by the impact crater population. While the specific details of crustal recycling and overturn on Venus remain contentious, a concensus has emerged that the planet was largely resurfaced, and the crater population reset, on the order of 300 to 500 Myr ago (Schaber et al. 1992; Phillips et al. 1992). Based on this average age, Arvidson et al. (1992) estimated that the rate of physical weathering in the lowlands is no higher than $\sim 10^{-3}\ \mu m\ yr^{-1}$ (or $\sim$0.5 m over 500 Myr), comparable to regolith formation rates on the Moon (Horz et al. 1991).

Chemical weathering on Venus can be studied by assuming that the surface and atmosphere are in thermodynamic equilibrium, and calculating the stability of various mineral assemblages on the surface based on the measured composition of the Venusian lower atmosphere (see the chapter by Fegley et al.). Mueller (1963) first proposed that the high surface pressure and temperature of Venus made it similar to metamorphic environments on the Earth, and as a result, (1) reaction kinetics might be expected to be geologically rapid, and (2) thermodynamic equilibrium between the atmosphere and the surface should be attained. Laboratory experiments on the gas-solid kinetics of anhydrite formation, pyrite decomposition, and oxidation of basalts on the surface of Venus have demonstrated that chemical reactions proceed geologically quickly. For example, the rate of chemical alteration of calcite to anhydrite is $\sim 1\ \mu m\ yr^{-1}$ (Fegley and Prinn 1989) and the rate of chemical alteration of pyrite to iron oxide is >1 cm yr^{-1} (chapter by Fegley et al.), or more than 7 orders of magnitude more rapid than the expected physical weathering. These estimates of weathering rate are only theoretical upper bounds, and do not necessarily imply a rapid rate of chemical erosion on the surface. The specific interaction between the surface rocks and the atmosphere has not been modeled, and a variety of possible mechanisms may occur on Venus.

In the broadest sense, two types of chemical reactions will occur at the surface on Venus: (1) volume-increasing and (2) volume-decreasing. Volume-increasing reactions, which include the formation of calcite from calcium oxide, reduce porosity and lead to sintering and cementing of the reaction products. These processes may effectively compete against physical weathering as they increase the grain size of materials, and it has been proposed that such reactions may be partly responsible for the relatively pristine condition of the Venus surface (Burke et al. 1994). Volume-decreasing reactions result in an increase in porosity and may speed physical weathering by causing the mechanical disintegration of surface rocks. Decomposition of pyrite, for example, results in a decreased volume of product (relative to reactant) and increased porosity (chapter by Fegley et al.). The extent to which individual chemical processes contribute to changes in the texture of the surface and produce soil is unknown, but we will address the observational evidence for sediment accumulation below.

B. Sediment Production and Redistribution

The surface of Venus lacks a deep regolith, primarily due to the relatively young age of the surface (less than ~500 Myr), the protection from meteorite bombardment afforded by the thick atmosphere, and the lack of major erosional action by wind or water. The Venera lander images demonstrate that fine debris (down to at least the cm-scale) does exist on Venus, and that the quantity and grain size of the material varies from site to site (Garvin et al. 1984). Weathering of the surface rocks by mechanical or chemical processes appears to produce material that is shallow, coarse, and relatively immobile. As noted above, the pristine state of many geologic features argues for a weathering rate of $<10^{-3}$ μm yr^{-1}, comparable to those found for the lunar surface. Such *in-situ* weathering should be most effective in the highlands, where slopes are relatively steep and we could expect a constant exposure of fresh surface rock. Analysis of mass movements within the highlands demonstrates, however, that most such deposits are dominated by bedrock collapses; no evidence for sediment slumps, flows, or falls has been found (Malin 1992). The Venera 9 site on the flank of Theia Mons contains a substantial population of surface rocks, but no apparent concurrent development of a major soil component. The global average dielectric constant is ~4.5, consistent with moderate-low density terrestrial basalts or more dense material with a very thin surficial soil layer (Pettengill et al. 1992; Ulaby et al. 1988).

Another possible source of fine material is impact crater formation, which produces ejecta deposits with a broad range of grain sizes and radial distances from the cavity (cf., Oberbeck 1975; McGetchin 1973). Young craters on Venus are characterized by radar-bright floors and parabolic patterns of low-backscatter, low-emissivity material. These parabolas extend for hundreds of km (typically to the west of the crater), and were evidently emplaced as airfall deposits from ejecta clouds thrown high into the atmosphere (Campbell et al. 1992; Schultz 1992). Grain sizes of materials in the parabolas are likely no greater than 1 cm, based on both the ability of the atmosphere to support the loaded cloud of hot debris and the surface roughness of the emplaced material. Izenberg et al. (1994) estimated that these features have a lifetime of a few tens of Myr based on a global mean cratering rate, which supports an average dispersion rate of $\sim 10^{-3}$ μm yr^{-1}. Many impact craters also have concentric, near-circular low-backscatter areas (Phillips et al. 1991). These regions may be covered with a shallow layer of fine material produced by shock comminution of the surface rock by the atmospheric blast associated with a bolide's entry (Schultz 1992; Ivanov et al. 1986). Areas of higher backscatter surrounding some craters may be regions where fine material has been swept from the surface or where coarse comminuted material is produced by the blast wave.

If the majority of craters form parabolas, concentric low-return haloes, or some combination of these features, then impact processes may contribute the bulk of fine-grained soil on the surface. This hypothesis is supported by the strong tendency for wind streaks and dunes to occur in relationship to craters (e.g., Aglaonice and Fortuna-Meshkenet dune fields), indicating that only this material is fine enough to be moved easily by the wind (Greeley et al. 1992). Similar wind streaks are not observed randomly about the plains, so any soil formed by *in-situ* weathering is probably more granular and immobile. Garvin (1990) calculated a possible sediment budget for Venus based on crater counts from the Venera 15 and 16 radar images, and suggested that very fine material ($<30\,\mu$m) would not likely be produced in adequate amounts to supply a global sedimentary layer. Large-scale coverage of the surface to depths observed at the Venera lander sites would require transport of particles up to 1 cm in size over large regions. While the Magellan data have confirmed the paucity of small craters shown by the Venera images, other mechanisms of impact-derived sediment formation have also been identified. Specifically, the large low-backscatter haloes and the parabolas represent styles of sediment generation and transport not included in typical crater ejecta models (see, e.g., Melosh and Schaller 1996). The issue of whether impact-produced sediments can dominate the global budget of such materials thus remains open.

A final possible source of fine material is explosive volcanism. The high Venus atmospheric presure inhibits the exsolution of volatiles from rising magma bodies, and thus limits pyroclastic eruptions to cases of high volatile content (and preferably higher elevation) (Garvin et al. 1982). While evidence for such eruptions is present (i.e., Maat Mons [Klose et al., 1992]), they are likely to be too limited to contribute a significant fraction of the global sediment budget.

Redistribution of sediment on Venus can occur by only two processes: mass movement (slumping) or wind transport. For the lowlands, topographic slopes are typically so small (on the order of 1° or less) that gravitational movement of fine soil is negligible. Steeper slopes in the highlands may create local sediment-collecting troughs, but these have not been directly observed. Greeley et al. (1992) found that the global pattern of wind streaks indicates neither a zonal nor a meridional circulation pattern. This suggests that many of the surface streaks may reflect the local winds at the time of crater formation, which is consistent with the arcuate wind features found concentric to many large impact craters (Schultz 1992). More recent work (chapter by Greeley et al.) demonstrates that the streaks do represent two populations: one indicative of Hadley cell circulation, the other linked to impact-produced transient winds.

In summary, the surface of Venus is likely comprised of relatively pristine bedrock, that undergoes a slow process of mechanical rubbling due to surface-atmosphere interactions. Such *in-situ* weathering may reduce blocky surface textures to more granular deposits, though again at a very slow rate. Fine soil accumulates predominantly as a result of impact crater formation, and this material can be moved by the wind, at least during subsequent nearby cratering events. High backscatter areas found surrounding some craters may thus be regions of coarse comminuted debris or areas stripped of all past mantling by the strong winds, while low backscatter concentric deposits may be regions where fine soil has been produced by atmospheric blast waves. Erosion in the highlands is still poorly understood, because topography and chemical processes in these areas are significantly different from those in the plains.

III. DERIVATION OF LOWLAND SURFACE PROPERTIES FROM MICROWAVE DATA

With the exception of the Venera and Vega lander sites, all estimates of the texture, density, and composition of the Venus surface are based on analysis of microwave data for backscatter and emission. A thorough characterization of the terrain requires analysis of both surface roughness and dielectric constant variations. In this section we discuss tools for such analysis and the results obtained from global mapping.

A. Surface Roughness

Radar backscatter is a function of both roughness at a variety of scales and the bulk dielectric properties of the target material. Roughness on scales that are large with respect to the wavelength can produce facet-like (quasi-specular) echoes, while roughness on scales close to that of the radar wavelength tends to produce diffuse returns (Hagfors 1970). Magellan used a 12.6-cm radar system to map the surface primarily in a horizontal-transmit, horizontal-receive (HH) polarization sense. Incidence angles varied from $\sim 20^{\circ}$ to 45° with latitude and radar viewing configuration. The measured power was converted to values of specific radar backscatter cross section.

Terrestrial radar data sets, such as those produced by the NASA/JPL AIRSAR system, provide a good reference point for understanding radar backscatter from natural surfaces and for comparison with Magellan data. A synthesized S-band (12.6-cm) HH radar image of Kilauea Volcano, Hawaii, is shown in Fig. 1, and the scattering behaviors for lava flows of varying roughness are presented in Fig. 2. There is a good separation in echo strength due to changes in lava texture for angles $>30^{\circ}$, which makes it possible to directly infer Venus surface roughness from Magellan data at similar viewing geometries (Campbell et al. 1993; Campbell and Campbell 1992; Gaddis 1992; Arvidson et al. 1992; Plaut 1991). At angles less than about 30°, the backscatter data suffer from an ambiguity between diffuse and quasi-specular scattering mechanisms which can effectively mask large differences in wavelength-scale surface structure (Campbell and Campbell 1992). Echoes from relatively smooth surfaces have angular scattering functions that drop rapidly from a very high nadir value, while rough surfaces exhibit a moderate radar return and a gentle decline in power with angle. For rocky terrains, these two types of angular scattering function cross one another near 30°, resulting in a diminished sensitivity to small-scale surface roughness.

The inference of relative surface roughness by comparison to terrestrial analogs requires a few caveats: (1) the surface dielectric constant is assumed to be relatively uniform among geologic units and is comparable for the Earth and Venus; (2) the Venusian surface is not covered to a large degree by fine soil; and (3) the response of the radar to roughness reflects only the statistical nature of the height fluctuations rather than some particular scatterer shape. The first assumption is verified by global mapping of bulk dielectric constant, which ranges from about 4 to 6 for most Venus lowland lava flows and plains, demonstrating that rock or closely packed debris dominates the surface (Pettengill et al. 1992; Campbell 1994). The second issue appears to be important only in areas of impact crater debris or volcanic mantling materials: porous material on a surface will tend to reduce the backscatter coefficient by lowering the dielectric contrast between the rock layer and free space and

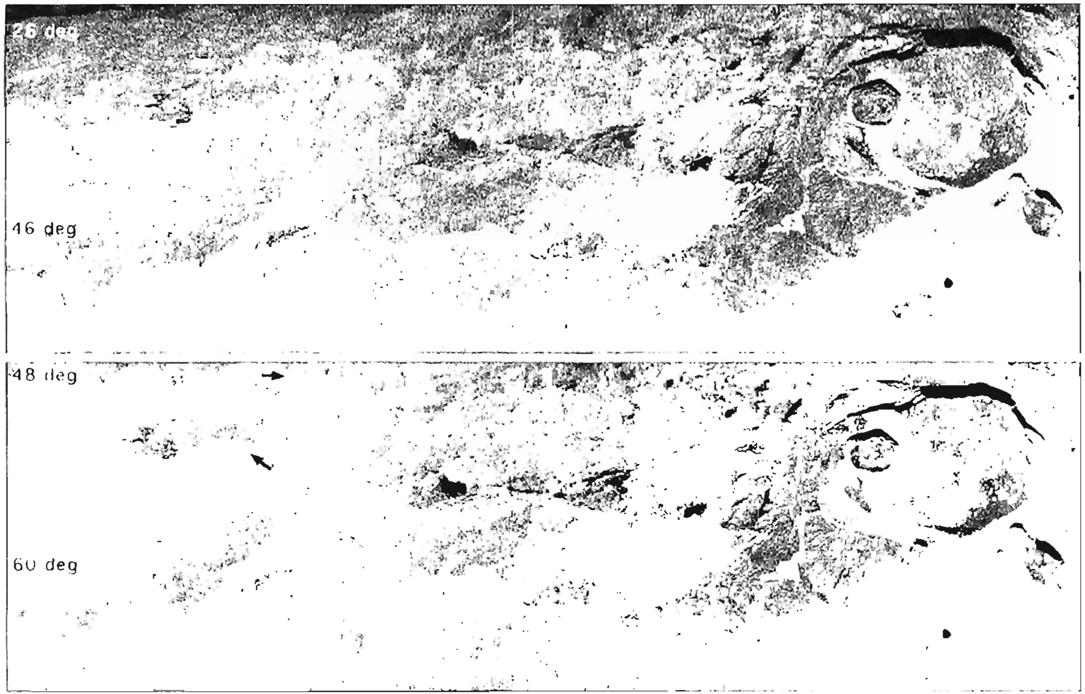

Figure 1. Radar images of the Kilauea Volcano summit area and Kau desert region in Hawaii, collected on two parallel flightlines which provide complementary incidence angle coverage. Data are synthesized S-band (12.6-cm) HH polarization, inferred from AIRSAR measurements at 5.7 and 24 cm. Image resolution 10 m/pixel; image width 21 km. Logarithmic scaling, with data normalized to the Muhleman scattering law applied to Magellan data for Venus. The range of incidence angles is marked along the side of each scene; radar flight direction is across the top of the image. Note that the rough a'a lava flows from the Mauna Iki complex, shown by black arrows in the lower scene, are indistinguishable from their smoother surroundings at a 26° incidence angle in the upper scene.

by attenuation within the fine-grained deposit. The third assumption merely states that natural surfaces tend to have random distributions of scattering centers (i.e., fields of rocks or cracks).

The terrestrial analog data can be used to discern levels of roughness among Venus surface units, and we use an example area to illustrate this methodology. A Magellan image for the area surrounding Sapas Mons (viewed at an incidence angle of ~45°) is shown in Fig. 3. The majority of plains regions surrounding Sapas Mons have backscatter values comparable to smooth pahoehoe flows in Hawaii (-20 dB$<\sigma_0<-9$ dB), consistent with their probable origin as large fissure-fed basaltic eruptions. Slow mechanical weathering may also contribute to the low roughness of these regions. Some areas do have considerably lower backscatter values, indicating either extremely smooth textures or the presence of fine-grained mantling material, which attenuates the incident energy. Several small lava flows on southeast Sapas Mons display this signature, as do a number of plains patches to the south of the edifice. The radar-dark flows on Sapas are younger than the surrounding plains, so it is likely that their smooth surfaces are indicative of the originally emplaced morphology rather than fine soil formed by *in-situ* weathering.

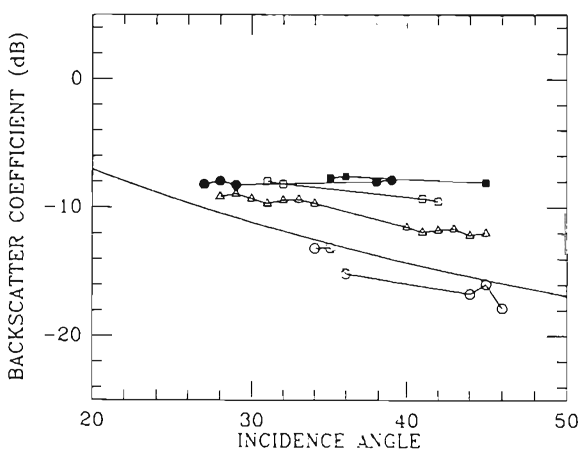

Figure 2. Plot of backscatter versus incidence angle for Hawaiian lava flows. HH polarization cross section values for 12.6-cm wavelength, interpolated from 5.7- and 24-cm AIRSAR measurements. Solid symbols are two a'a lava flows made up of jagged or platy textures; remaining three plots are for progressively smoother pahoehoe units. Solid line is average backscatter behavior for Venus (Muhleman law). Note the drop in overall power at high angles and the steeper decline with angle for smoother surfaces.

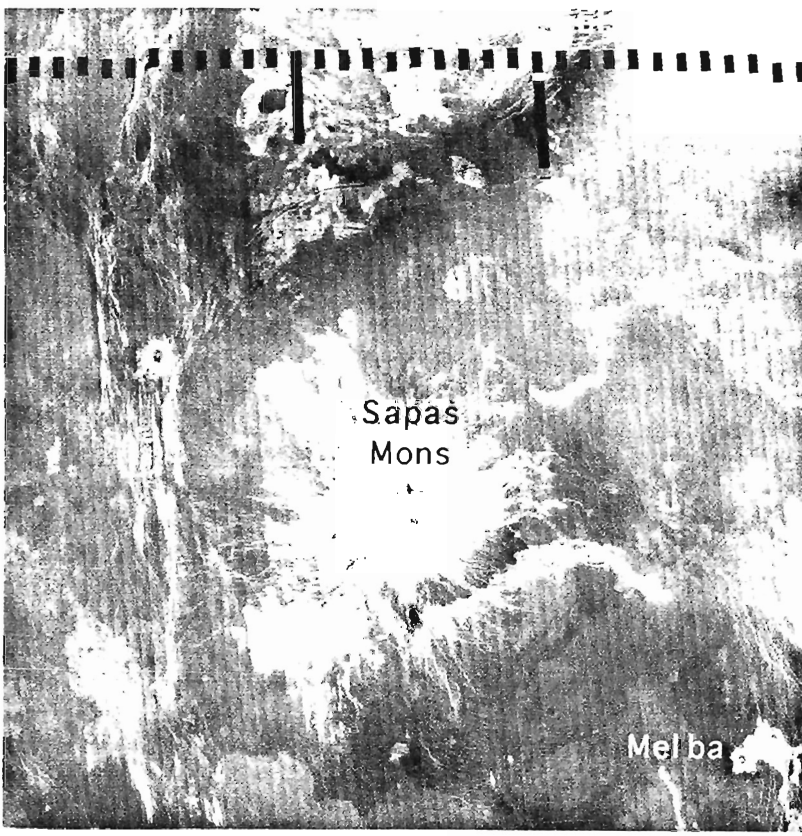

Figure 3. Magellan image of region surrounding Sapas Mons (3.5–16.5°N, 181.4–194.6°E). The high backscatter values for the summit area of Sapas Mons are due to increased reflectivity rather than to ubiquitously high roughness. Note the low radar backscatter from areas covered by fine ejecta from Sitwell crater.

Analysis of global roughness behaviors illustrates that much of Venus is very smooth, relative to young terrestrial basaltic flows, at both the meter and tens of meter scales (Ford and Pettengill 1992; Campbell and Campbell 1992). Many large Venus plains regions have scattering functions which drop more rapidly with incidence angle than even smooth terrestrial lava flows. Given the lack of deep soil layers at the Venera sites, it is most likely that the low backscatter values and steep angular scattering functions reflect a lack of significant blocky or hummocky textures in the plains. Arvidson et al. (1992) observed that some plains regions have subdued lobate flows which appear to be stratigraphically older than flows with similar shapes but higher radar backscatter. This indicates that weathering processes reduce the meter-scale roughness, to the extent that it originally exists, of plains basalt flows over long periods of time.

An arcuate band of very low radar return occurs north of Sapas Mons. Examination of the image data shows that the reduced echo from these plains is due to a covering of fine-grained impact ejecta from the crater Sitwell (16.68°N, 190.35°E, 34.5 km diameter). As noted by several authors (Schaber et al. 1992; Schultz 1992; Campbell et al. 1992), these dark haloes typically surround a relatively unmodified or radar-bright central area closer to the parent crater, where the increased brightness is due to either formation of rough comminuted material or the removal of pre-existing fine mantling debris. The atmospheric blast wave associated with bolide entry plays a major role in forming these concentric deposits, and the resulting distribution of distal impact material on Venus differs considerably from that for an airless body.

Areas of higher backscatter occur in the near-rim ejecta blankets of impact craters, but also in some crater outflow deposits (note the 24-km crater Melba in the southeast corner of the image). Numerous lava flows from Sapas Mons have quite high surface roughness, suggesting either high effusion rates or viscous magma. A survey of other large edifices shows that such rough flows are uncommon on Venus, with most shield volcanoes built up of more moderate- to smooth-surfaced flows consistent with low-volume eruption rates or low magma viscosity. The highest σ_0 values in the example region occur on Sapas Mons and along the ridged terrain in the northeast corner at elevations above ~6054 km radius. As discussed below, these regions have enhanced Fresnel reflectivities, probably due to the formation of a high-dielectric (low emissivity) surficial coating. Their elevated backscatter is thus not a direct indicator of high roughness, and additional work is required to define textural changes in highland areas.

B. Dielectric Constant

The complex dielectric constant (permittivity) of the surface determines its reflectivity and the degree of attenuation experienced by radar energy passing through the material. Several approaches can be used to derive estimates of the dielectric constant from Magellan data. The Magellan altimeter system collected backscatter data for the surface at small angles of incidence ($<10^\circ$) and these echoes were modeled using the Hagfors expression to derive estimates of reflectivity ρ and rms slope (Ford and Pettengill 1992; Tyler et al. 1992). A correction for diffuse scattering based on the SAR echo at large incidence angles was added to refine the estimates of ρ.

The Magellan radar receiver was also used to measure the microwave thermal emission from Venus. Emissivity is defined as the ratio between the observed emitted radiation and that expected for a Planck blackbody at the same kinetic temperature (determined for Venus from a standard model of temperature lapse with elevation) (Pettengill et al. 1992). The microwave emission from a surface is controlled in part by the dielectric constant, with higher values of directional hemispherical reflectivity leading to lower values of emissivity at the same viewing geometry. For a perfectly smooth surface, the emissivity E at emission angle ϕ and real dielectric constant ϵ is given by the Fresnel transmission coefficients (Stratton 1947):

$$E_h = T_h = \frac{\sin 2\phi \sin 2\theta}{\sin^2(\theta + \phi)} \tag{1}$$

$$E_v = T_v = \frac{\sin 2\phi \sin 2\theta}{\sin^2(\theta + \phi)\cos^2(\phi - \theta)} \tag{2}$$

$$\theta = \sin^{-1}\left(\frac{\sin\phi}{\sqrt{\epsilon}}\right) \tag{3}$$

where the h and v subscripts refer to horizontal and vertical polarization states. The emissivity from a rough surface has not been rigorously modeled, so an approximate behavior is often used (Hagfors 1970; England 1975; Ulaby et al. 1982). As the surface becomes rougher at the scale of the radar wavelength, the emissivity is assumed to move toward the average of the plane-surface transmission coefficients for the two polarizations (Ulaby et al. 1982; Campbell 1994). At lower dielectric constants or smaller values of ϕ the range of emissivity between smooth and rough surfaces decreases (chapter by Pettengill et al., Fig. 1). For emission angles of less than ~30°, the difference in emissivity between a perfectly smooth and rough surface is negligible, so we can use the Fresnel expressions given above to solve for the dielectric constant (the "plane surface" assumption) from E_h or E_v. Volume scattering and emission processes are neglected in this approach.

A method for refining the dielectric constant estimate in rough areas was proposed by Campbell (1994) from analysis of the global correlation between SAR HH backscatter and H-polarized emissivity. For areas below ~6054 km in radius, these parameters are systematically correlated, implying (1) a random distribution of dielectric constant with texture, and (2) a mutual increase in backscatter and emissivity with wavelength-scale roughness. By assuming that the emissivity varied between the smooth- and rough-surface values as the backscatter increased, an empirical model for roughness and dielectric constant was derived. This technique appears to suppress roughness-related changes in emissivity across the tesserae and other rough areas, but the results are dependent upon the model assumptions.

Another method for dielectric constant estimation involves use of dual-polarization emissivity data. Magellan collected global emission measurements for Venus in the horizontally polarized sense, but vertically polarized values for emissivity are also available for a few hundred orbits. The average emissivity can be shown to be less sensitive to roughness than either individual component; and Arvidson et al. (1994) used this behavior to map dielectric variations across a swath of Ovda Regio. Nearly all approaches to dielectric constant estimation assume a single-dielectric interface and a simple separation of the surface into plane and rough components. Where mixed dielectric values occur, such as for the case of partial mantling by fine soil, the derived dielectric constant will reflect an average of the two components

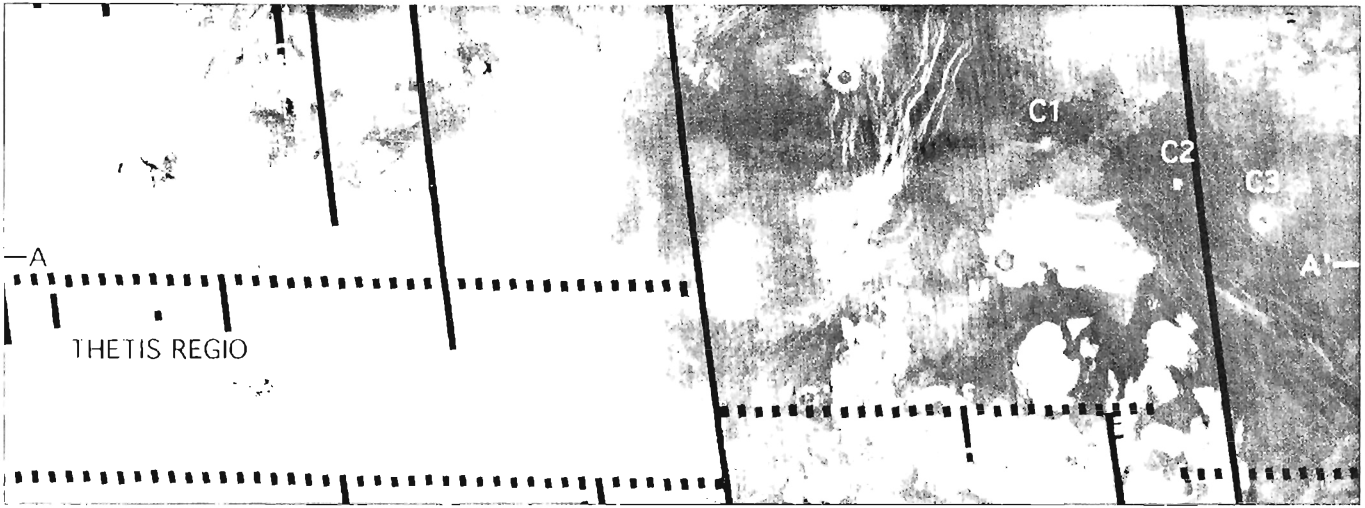

Figure 4a. Radar backscatter image for the region between Thetis Regio and Markham crater (indicated by an M). Area covered is 10°S–2°N, 132–164°E. The three smaller impact features discussed in the text are noted by C1, C2, and C3 designations. Note the difference in radar brightness between tessera regions at lower elevations, such as those south of Markham, and plateaus in Thetis Regio which exceed 6054 km in radius.

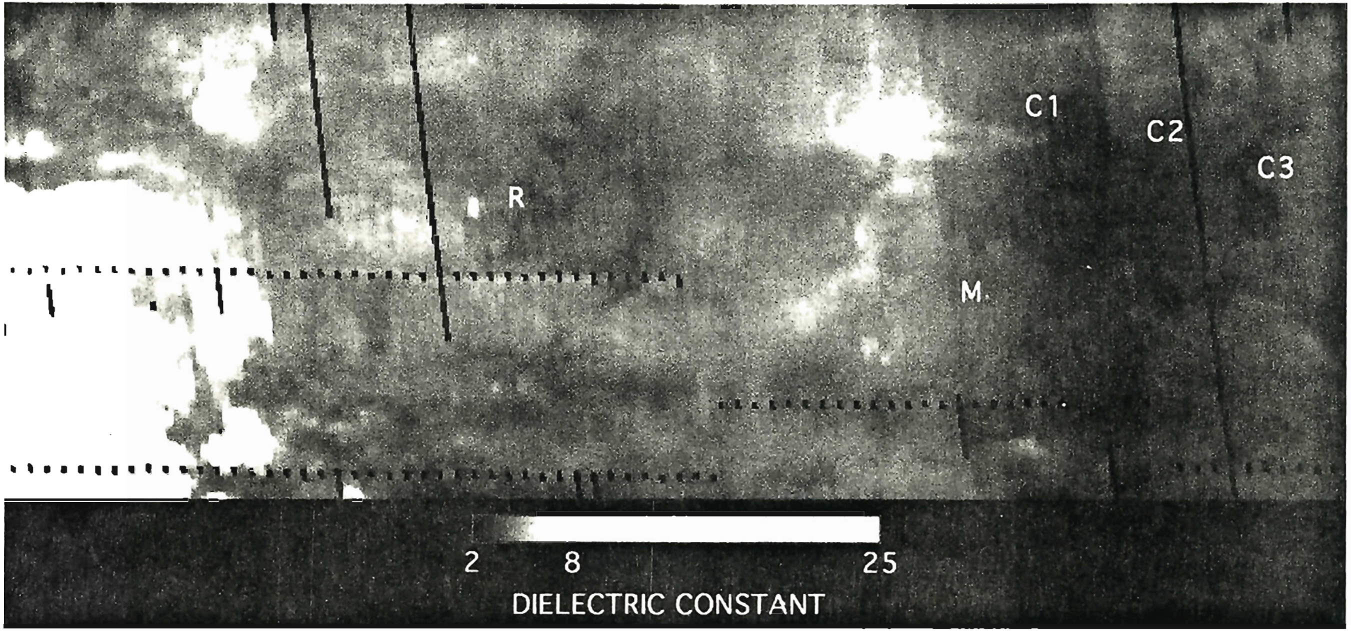

Figure 4b. Dielectric constant map for the region between Thetis Region and Markham crater (indicated by an M).

weighted by their areal distribution. The effect of such partial mantling on the radar backscatter and emission will be considerably different, so care is required when making roughness estimates for regions of potential soil cover.

Despite these caveats, the methods decribed above can yield reasonable estimates of the dielectric properties of the Venus surface. To illustrate the range of dielectric properties found on Venus, we selected an area that includes eastern Thetis Regio and Markham crater (Fig. 4). Dielectric constants were derived from the global map of Campbell (1994). The topography, radar backscatter, emissivity, and model-derived dielectric constant values for an east–west profile (A-A′) through Markham are shown on Fig. 5.

The plains, typified by the area between a small ridge belt (R on Fig. 4) and Markham crater, are characterized by gently undulating topography, moderate to low backscatter, and a narrow range of dielectric values (ϵ = 3–5). Across Venus, dielectric constants for the plains tend to stay within the range from 3 to 6, consistent with values found for low-moderate density terrestrial basalts (Ulaby et al. 1988). Variations in dielectric constant among plains-forming units may be due to minor variations in oxide mineral content (e.g., ilmenite) or to differing amounts of surficial fine material. Changes in the proportions of minerals such as ilmenite have been shown to have a significant effect on the dielectric constant of lunar basalts (partly through the increased bulk density of the rock) (Carrier et al. 1991), while fine superposed material will attenuate the incident energy in a manner which varies with the loss properties of the soil and its depth. Lava flows from volcanic edifices display a slightly larger range in dielectric constant, with values reaching 8 to 9. The highest dielectric flows typically appear to be younger than other deposits based on superposition, again suggesting that over time these flows experience chemical weathering (i.e., oxidation of metallic minerals) or soil emplacement due to mechanical weathering or impact ejecta deposition. The ridge belts and tessera terrains within the lowlands (<6054 km radius) have no strong dielectric differences from the plains, indicating that these areas are probably deformed basaltic material. The large radar echoes from the ridge belts along the profile arise from a combination of folding (which lowers the local incidence angle) and meter-scale roughening due to this deformation.

Distal impact crater ejecta deposits on Venus have a marked dichotomy in their dielectric properties. Some fine-grained layers have ϵ values of 2 to 3, consistent with low-density rock powders. These deposits mantle the underlying terrain and subdue the backscattered return. In contrast, the parabolic ejecta from apparently young craters (Campbell et al. 1992) is typically too thin to have a significant effect on the radar echo, but can have dielectric constant values of 6 to 8 (early observations of these properties were made by Jurgens et al. 1988). This implies that the fine debris has a significant component of metallic minerals, possibly formed during the impact melting process. Conversely, many of the large circular radar-dark haloes around craters have no associated emissivity anomaly.

A number of impact-related features occur in the area shown in Fig. 4,

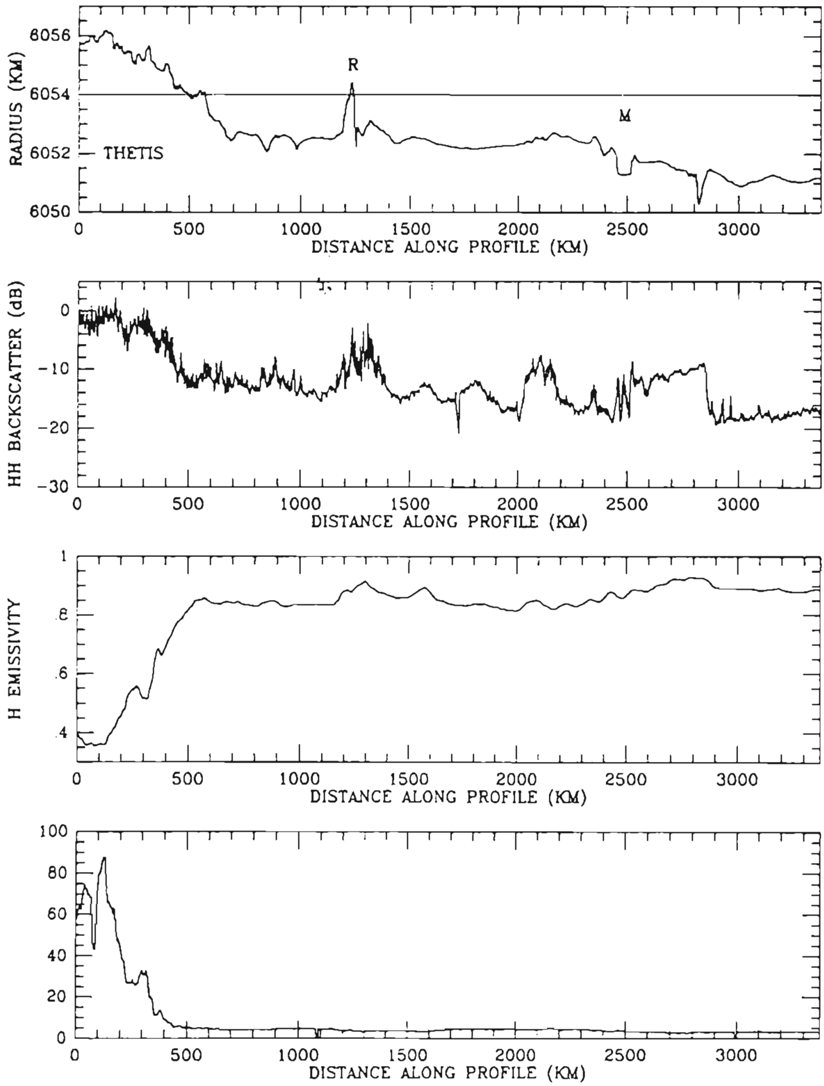

Figure 5. Average values for topography, backscatter cross section, H-polarized emissivity, and model-derived dielectric constant (from Campbell 1994) for a 25-km wide profile (A-A′ in Fig. 4) through Thetis Regio and Markham crater (noted by an M). A small ridge belt west of Markham is indicated by an R. Note the rapid rise in dielectric constant (reduction in emissivity) and backscatter cross section for areas above 6054 km in radius (shown by dotted line). The abrupt drop in topography at the distal margin of the outflow may be a spurious value, based on poor near-nadir echoes from the very rough surface.

and demonstrate the degree to which such deposits can vary in their properties. Figure 6 presents a closer view of some of these impacts deposits. Markham (indicated by an M on Figs. 4 and 6) is a 60-km diameter crater with a partial peak ring complex, low-return floor materials, and an east-trending outflow deposit which formed contemporaneously with the ejecta blanket (Johnson and Baker 1994; Schultz 1992). None of the units associated with Markham can be distiguished clearly from the plains on the basis of their dielectric constant, indicating that any mineralogical or porosity changes (i.e., fine-grained mantling deposits) related to the impact event have been eliminated by aeolian or chemical weathering. The high radar returns from the Markham crater outflow deposit thus indicate a rough surface texture.

Figure 6 also illustrates flow-like features northeast of Markham which have relatively subdued radar signatures relative to the younger crater outflow deposit. In many plains areas, a similar pattern can be observed, with stratigraphically older units exhibiting lower or less varied radar backscatter than apparently younger lobate deposits. Such behaviors may imply that: (1) plains areas with few discernible lobate features are older and weathering has reduced the meter-scale roughness of the surface, or (2) plains may form by a variety of eruption styles, some of which produce discernible lobate forms and some which lead to relatively featureless smooth surfaces. Use of the degree of lobate texture in the plains to infer relative age is thus ambiguous unless supported by clear stratigraphic relationships.

North of Markham is a 4-km crater (C1 on Fig. 4) with a westward-pointing parabolic deposit whose bulk dielectric constant reaches values of $\sim$7. While such values can be satisfied by relatively dense terrestrial basalts, the parabolic deposits are assumed to be fine-grained material that thinly mantles the plains (Campbell et al. 1992; Schultz 1992). Such porous deposits would typically have lower permittivity than the solid parent rock, and the increase in dielectric constant may be due to reduction of metallic minerals such as iron oxides during the impact melting and recondensation process (Campbell 1994; Brackett 1995). Reduced materials might have a limited lifespan at the Venus surface, but their inclusion within glasses may slow the re-oxidation process. The radar backscatter of the parabola is lower only in the distal reaches of the deposit, indicating a possible thickening of the material (or greater smoothing due to finer grain sizes) to the west. An 11-km crater (marked C2 on Fig. 4) northeast of Markham lacks any emissivity signature. This emphasizes the ephemeral nature of the fine-grained parabola-forming material, which has evidently been removed from this crater by aeolian processes (Izenberg et al. 1994). Another impact feature east of Markham (C3 on Fig. 4) has a circular annulus of apparently low dielectric material ($\epsilon = 2$), but this is an artifact of the solar specular reflection observed during the Magellan mapping Cycle 1 (Pettengill et al. 1992).

IV. HIGHLAND SURFACES

Areas at elevations above $\sim$6054 km radius on Venus typically have high backscatter cross section, high microwave Fresnel reflectivities, and low emis-

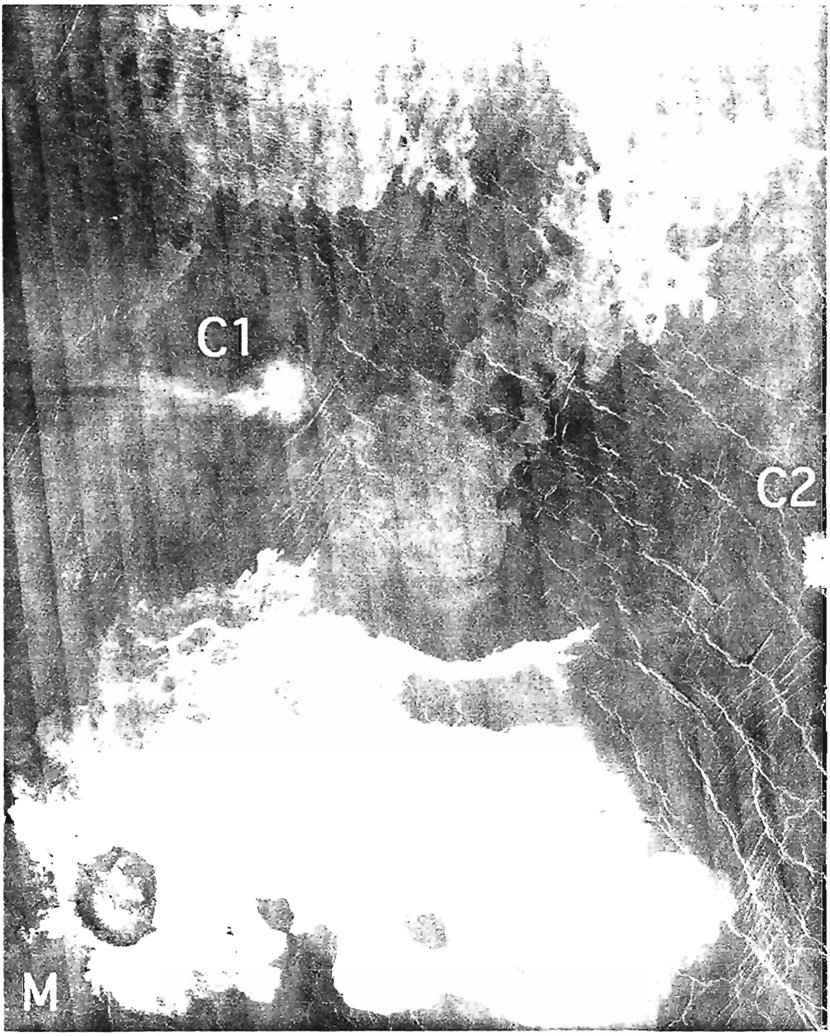

Figure 6. Closeup view of Markham crater (60-km diameter) and nearby impact features discussed in text. Designations correspond to those on Fig. 4.

sivity (Pettengill et al. 1982,1988,1992). At the highest elevations (greater than about 6058 km radius), emissivity shifts back toward values consistent with bare rock (Klose et al. 1992; Arvidson et al. 1994). The progressive decrease in emissivity (increasing dielectric constant) is directly correlated with increasing elevation, and this behavior is seen across the planet, with dielectric values reaching 250 or more in the Maxwell Montes (chapter by Pettengill et al.). The dotted line in Fig. 5 indicates the approximate elevation at which the dielectric enhancement occurs for Thetis Regio; note that model-derived values for ϵ of up to 90 occur in this region. The estimation of dielectric constant for highland areas based on the models discussed above is still tentative, because the effect of enhanced multiple scattering on backscatter and emission from such highly reflective terrains is poorly understood.

Some areas above the nominal elevation for dielectric enhancement (~6054 km) exhibit little or no such change in their backscatter and emission properties. Most notable is the summit of Maat Mons (1.5°N, 194°E), which reaches a maximum height of 9 km above the datum but has a model-derived dielectric constant of 6 to 8 (Klose et al. 1992; Campbell 1994). The lack of a dielectric enhancement for the summit of Maat has been interpreted to indicate a young age for the surface lava flows, based on the assumption that the highland chemical changes occur ubiquitously and on a short time scale (Klose et al. 1992; Robinson and Wood 1993; Robinson et al. 1995). While a youthful surface near the summit of Maat Mons and in other low-ϵ highland areas is plausible, the current lack of a candidate mineralogy and reaction sequence for the weathering process argues for caution. Alternative hypotheses include the inability of the loading phases or cold-trapped materials to occur on lavas of certain chemistries, or the presence of fine-grained ash layers at the surface which depress the apparent dielectric constant.

The enhanced backscatter cross section in the highlands has been interpreted as due to the increasing Fresnel reflectivity of the surface materials, but surface roughness also plays a role, with the tessera areas generally having a higher degree of rocky texture than the plains. Global analyses show that, to first order, the value of the dielectric constant has little relation to the type of landform (smooth intra-tessera plains, tessera, or ridges), indicating that the emissivity change occurs due to a ubiquitous surficial coating or mineralogic change (Klose et al. 1992; Arvidson et al. 1992, 1994; Campbell 1994). Whether this chemical process influences the surface roughness remains an open issue.

A variety of possible scattering mechanisms and dielectric constant variations could account for the observed highland properties, but only a few are consistent with the geologic evidence and the analysis of bistatic radar echoes (chapter by Pettengill et al.). Tryka and Muhleman (1992) proposed that high dielectric scatterers imbedded in a low-loss soil could permit efficient multiple scattering, while Pettengill et al. (1992) proposed that wavelength scale voids in a basalt matrix could also account for the observations. Recent bistatic observations of select highland regions (chapter by Pettengill et al.) indicate the existence of a Brewster angle, i.e., a bistatic angle of observation at which vertically polarized scattered radiation disappears. This phenomenon is associated exclusively with surface scattering. Furthermore, the value of the Brewster angle is indicative of the dielectric constant of the surface, which is inferred to be on the order of 100 or more, consistent with values extracted from emissivity observations if simple Fresnel emission is assumed. Volume scattering models also require a background medium (i.e., the soil) which is nearly transparent to the radar, whose ubiquitous presence in the Venus highlands would be problematic (Wilt 1993). All current evidence thus points to a surface scattering mechanism for the highlands.

There have been several surface-scattering models proposed to explain the high radar reflectivity of the Venus uplands. The earliest was the loaded dielectric model, which proposed that iron sulfide or oxide comes into thermochemical equilibrium only in the highlands because of the strong altitude-dependence of pressure and temperature that exist on Venus (Pettengill et al. 1982; Klose et al. 1992). The presence of a conducting phase interspersed within a rock-like matrix would give rise to a very high effective dielectric constant and therefore a low observed emissivity. Recent experimental kinetic work suggests that pyrite (FeS_2) is not a viable candidate for a loaded dielectric phase because it is thermodynamically unstable over the entire range of Venusian surface conditions (Fegley et al. 1993*a*,*b*,1995; Klingelhofer et al. 1994). Any candidate phase must be (1) highly conductive, (2) present in significant quantities (>10% by volume), and (3) come into thermochemical equilibrium between elevations of ~6054 and 6058 km.

Fegley et al. (1992) suggested that perovskite ($CaTiO_3$), a thermodynamically unstable mineral phase under all Venusian surface conditions, might be a viable candidate material for the loading phase. Perovskite is known to occur in terrestrial alkaline basalts, and dielectric constant measurements indicate values of 1100 to 2200 at frequencies of 10 kHz (Timco 1977). The decomposition of perovskite is likely to be governed by an Arrhenius relationship, with the rate of decomposition proportional to temperature. The gradual decrease in emissivity with elevation can thus be explained by the temperature dependence of decomposition kinetics. The return to normal emissivities at the highest elevations is attributed to an abrupt phase transition to rutile (TiO_2) and flourite (CaF_2) caused by reaction with atmospheric HF (Fegley et al. 1992). Further experimental work is needed to assess the thermodynamic stability of perovskite, the kinetics of perovskite decomposition, and the dielectric constants of perovskite under Venusian conditions.

Shepard et al. (1994) proposed that the high dielectric constants observed in the highlands are due to the presence of ferroelectric minerals (many minerals in the perovskite family are ferroelectric). Ferroelectric minerals have unusual dielectric properties; below a compositionally dependent Curie temperature, the dielectric constants are in the range of 10 to 100. However, at the Curie temperature, the dielectric constants dramatically increase, often to values as high as 100,000 (Burfoot 1967). Mixing models for two-component mixtures of dielectrics indicate that as little as 0.1% by volume of a ferroelectric mineral phase can explain the lowest emissivities observed on Venus (Shepard et al. 1994). This model explains the return to normal emissivities as the altitude at which the surface temperature drops below the Curie point. The primary weakness of the ferroelectric model is that no single phase has yet been identified as a strong potential candidate; in fact, most ferroelectric phases are considered exotic by terrestrial standards.

Brackett et al. (1995) proposed that high-dielectric metal halides and chalcogenides are deposited in the highlands and are responsible for the observed low emissivities and high backscatter cross sections. They proposed that the high vapor pressures of metal halides and chalcogenides on Venus, coupled with the altitude dependent temperature gradient, lead to the diffusive transport of highly volatile metal phases from the hot lowlands to the (relatively) cold highlands. Deposition rates are highly variable (up to 1 μm yr^{-1}) and depend primarily upon the volatility of the phase. A sufficiently thick layer of these materials (i.e. mm to cm) deposited on existing surfaces could produce emissivities and backscatter cross sections similar to those observed. The bistatic observations of Pettengill et al. (see their chapter) indicate that the material responsible for the high radar reflectivities may be confined to a thin surface layer, and thus strongly favor this model. The increasing abundance of metal phases with decreasing temperature (i.e., increasing elevation) is consistent with the observed altitude dependent behavior of emissivity and backscatter cross section. However, the trend back toward normal emissivity at the highest elevations is more difficult to explain, and a specific phase has yet to be identified as a strong potential candidate.

To summarize, the observations to date strongly suggest that the low emissivities and high radar backscatter cross sections in the highlands are caused by a surface scattering and emission phenomenon. Of the four models currently proposed, each has strengths and weaknesses. The loaded dielectric model suffers due to the lack of a proposed thermodynamically stable conductive phase and the large quantity of conductive material required to produce the observed emissivities. The perovskite and ferroelectric models are related and may be considered together. Ferroelectric phases explain the observed trends in emissivity with elevation, and the return to normal emissivities at the highest elevations, very simply. However, the geochemistry of appropriate ferroelectric and/or perovskite phases has yet to be adequately explained. Perhaps the strongest of the hypotheses at this point is the metal phase deposition model, which is plausible given the current understanding of Venusian atmospheric chemistry. At least one set of observations from bistatic experiments seems to favor this model over the others. However, a specific phase has yet to be identified as a strong candidate and much geochemical work remains before this can occur. Inference of possible relative ages for geologic units in the highlands based solely on their emissivity is speculative at present, because the role of original rock chemistry in the development of loaded dielectric phases, ferroelectric minerals, or the growth of a metal phase by cold trapping is unknown.

V. SUMMARY AND FUTURE DIRECTIONS

The lowland plains of Venus, which make up more than 80% of the surface area of the planet, are characterized by primary volcanic, impact crater, and tectonic landforms which are only very slowly modified by in situ weathering. Weathering rates on Venus are orders of magnitude slower than those on Earth, and are comparable to erosional processes on the lunar surface. If Venus was resurfaced on the order of 500 Myr ago, then the various weathering effects must operate at less than $\sim 10^{-3}\ \mu m\ yr^{-1}$ to retain the pristine appearance of so many landforms. This estimate is supported by the distribution of fine-grained parabolic deposits from impact craters, which survive for several tens of Myr despite a very shallow depth. Resurfacing of the planet within the last 500 Myr and slow weathering processes have prevented the development of a lunar-like regolith or the fine dust which dominates the Martian surface.

In contrast to the other terrestrial planets, Venus presents a relatively straightforward view of how different features were created, and successive periods of tectonic or volcanic overprinting can often be identified (see, e.g., Solomon et al. 1992; Senske et al. 1992; Campbell and Rogers 1994). Lowland surface dielectric constants of 3 to 8, the absence of widespread wind-related features not associated with craters, and the lack of observed sediment mass movements, argue that fine soil does not develop rapidly under Venus conditions, and that the surface is composed to a much larger degree by bare rock and coarse fragmental debris than that of the Moon, Mercury, or Mars. Fine material is created during impact cratering (as part of the crater excavation and as a consequence of atmospheric blast waves), and is redistributed across the planet by upper-level winds during the ejection process and by global or crater-related local winds after deposition. This source likely constitutes the bulk of the very fine soil component on the lowlands surface. The radar properties of the highlands can be explained by surface scattering from a high-dielectric interface, but identification of a specific phase which produces this effect within the required narrow band of elevation remains a problem.

The Magellan mission provided a broad framework for understanding geologic processes on Venus. A number of important issues remain, however, which cannot be addressed solely with current data: (1) What is the total budget of sediment on the surface of Venus? (2) What is the role of chemical weathering, in terms of cementing and lithification, in the preservation of Venusian landforms? (3) What is the specific material which causes the high surface dielectric constant in the uplands? Does the formation of this material alter the surface texture in any way? (4) What is the nature of the dielectric enhancement associated with parabolic crater ejecta deposits and some crater floors? (5) How does the presence of the dense atmosphere affect the impact process, and to what extent can atmospheric blast waves comminute the upper surface? (6) What information, if any, on the surface today records the past climate and activity of the planet? Future Earth-based observations of Venus may answer some of these questions, but further understanding of most problems will come only from new lander (or near-surface) missions that focus on the geology, chemistry, and mineralogy of the surface materials.

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