AEOLIAN PROCESSES ON VENUS*

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Abstract. In this pre-Magellan review of aeolian processes on Venus we show that the average rate of resurfacing is less than 2 to 4 km/Ga, based on the impact crater size frequency distribution derived from Venera observations, reasonable values of the impact flux, and the assumption of steady state conditions between crater production and obliteration. Viscous relaxation of crater topography, burial by volcanic deposits, tectonic disruption, chemical and mechanical weathering and erosion, and accumulation of windblown sediments probably all contribute to resurfacing. Based on the rate of disappearance of radar-bright haloes around impact craters, the rate of removal of blocky surfaces has been estimated to be about 10^{-2} km/Ga. Pioneer-Venus altimetry data show that the average relative permittivity (at 17 cm radar wavelength) of the surface is too high for exposure of soils $\geq$10 cm deep, except for ~5% of the planet located primarily in tessarae terrains. The tectonically disrupted tessarae terrains may be sites of soil generation caused by tectonic disruption of bedrock and the presence of relatively steep slopes, or they may be terrains that serve as traps for windblown material. The overall impression is that Venus is a geologically active planet, but one dominated by volcanism and tectonism. On the other hand, theoretical considerations and experimental data on weathering and transport of surface materials suggest rather different conditions. Thermochemical arguments have been advanced that show: (1) CO_2 and SO_2 incorporate into weathering products at high elevation, (2) transport of weathered material by the wind to lower-elevation plains, and (3) re-equilibration of weathered material, releasing both CO_2 and SO_2. In addition, kinetic data suggest a rate of anhydrite formation of 1 km/Ga, a value comparable to the soil erosion rate on Mars, a planet with an active aeolian environment. Experiments and theoretical studies of aeolian processes show that measured surface winds are capable of moving sand and silt on Venus. Assuming that there is a ready sand supply, the flux could be as high as 2.5×10^{-5} g/cm/s, a value comparable to desert terrains on Earth. In an active aeolian abrasion environment, sand grains could have lifetimes $<10^3$ years. In addition, comminuted debris may be cold-welded to surfaces at the same time as abrasion is occurring. Magellan altimetry and SAR observations should allow assessment of which model for venusian surface modification (active vs. inactive surficial processes) is correct, given the global coverage, high spatial resolution, the calibrated nature of the data, and the potential during extended missions of acquiring multiple SAR views of the surface.

1. Introduction

Knowledge of the Venusian surface environment was poor until return of data from spacecraft. Nonetheless, Earth-based observations revealed the approximate composition, temperature, and density of the atmosphere, and enabled speculation on the nature of the surface and the potential for aeolian processes (Ronca and Green, 1970). Sagan (1975), Hess (1975), Iversen *et al.* (1976), Iversen and White

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(1982), and Greeley *et al.* (1984a) predicted the minimum winds required to entrain particles on Venus, based principally on theory or extrapolation from laboratory experiments performed under Venusian conditions. Venera lander spacecraft returned images of the surface that showed the presence of small grains and measured winds of sufficient strength to move them (Florensky *et al.*, 1977a). Pioneer-Venus provided additional data on the atmosphere, including measurements of the winds (Counselman *et al.*, 1979), as did the balloons inserted into the atmosphere during the Vega Mission (Blamont *et al.*, 1986). Thus, there are several lines of evidence suggesting aeolian processes on Venus, as reviewed by Kuzmin (1989).

Given the possibility of aeolian transport of surface materials, several major questions may be posed about the nature of aeolian processes on Venus and their role in the evolution of the surface and atmosphere, including:

(1) What is the nature of particle movement by wind on Venus? What is the rate of particle transport? Are the velocities and trajectories of entrained particles sufficiently energetic to cause abrasion of rocks and concomitant particle attrition and comminution?
(2) What is the sedimentary 'budget' on Venus if materials are transported by wind? Do certain regions (e.g., highlands) act predominantly as source areas while other regions (e.g., plains) are deposition sites? How does the global aeolian system influence weathering and erosion processes, and the general 'resurfacing' of the planet?
(3) Is the transported material in sufficient quantity on a regional basis to cause significant chemical changes of surface deposits and to affect the atmospheric composition by subsequent gas-solid reactions?
(4) Does the transport of material give rise to familiar aeolian features such as ripples and dunes? If so, what are the characteristics of these sedimentary features? Are there sedimentary deposits? How thick are they and do they suggest that current conditions have prevailed through geological time?

Answers to these questions have implications for several aspects of the surface history of Venus. For example, it has been suggested that aeolian processes may be responsible for the transport of fine-grained weathering products from the highlands into low regions to form some of the extensive plains inferred from Pioneer-Venus altimetry data (Warner, 1980; McGill, 1983). However, studies of existing radar data suggest that the surface of Venus has little in the way of sedimentary cover (e.g., Pettengill *et al.*, 1988), and that volcanism and tectonism are largely responsible for landforms on the planet (e.g., Barsukov *et al.*, 1986). In this review we: (a) consider the Venus observations relevant to surface processes, (b) outline the laboratory simulations and theoretical considerations of the effects of windblown particles on Venus, and (c) discuss plausible models for the roles that aeolian processes may have played on the planet. We then pose potential observations to be made via Magellan and future spacecraft to resolve unanswered questions regarding aeolian processes on Venus.

2. Observations of the Surface and Atmosphere

As reviewed by Saunders (1987) and Basilevsky and Head (1988), spacecraft have returned images from the surface of Venus for four lander sites, provided radar images and data on global topography from orbit, and measured atmospheric wind speeds, composition, and surface pressure. In addition, the Arecibo and Goldstone radiotelescopes have been used during selected inferior conjunctions to obtain backscatter images (and altimetry, from Goldstone) over parts of the Earth-facing hemisphere of Venus (e.g., Saunders and Malin, 1977; Campbell and Burns, 1980; Campbell *et al.*, 1984; Jurgens *et al.*, 1988; Arvidson *et al.*, 1990). In this section we summarize the results from Earth-based, orbiter, and lander observations, focusing on inferences that can be made about the surficial geology of Venus and the resurfacing history.

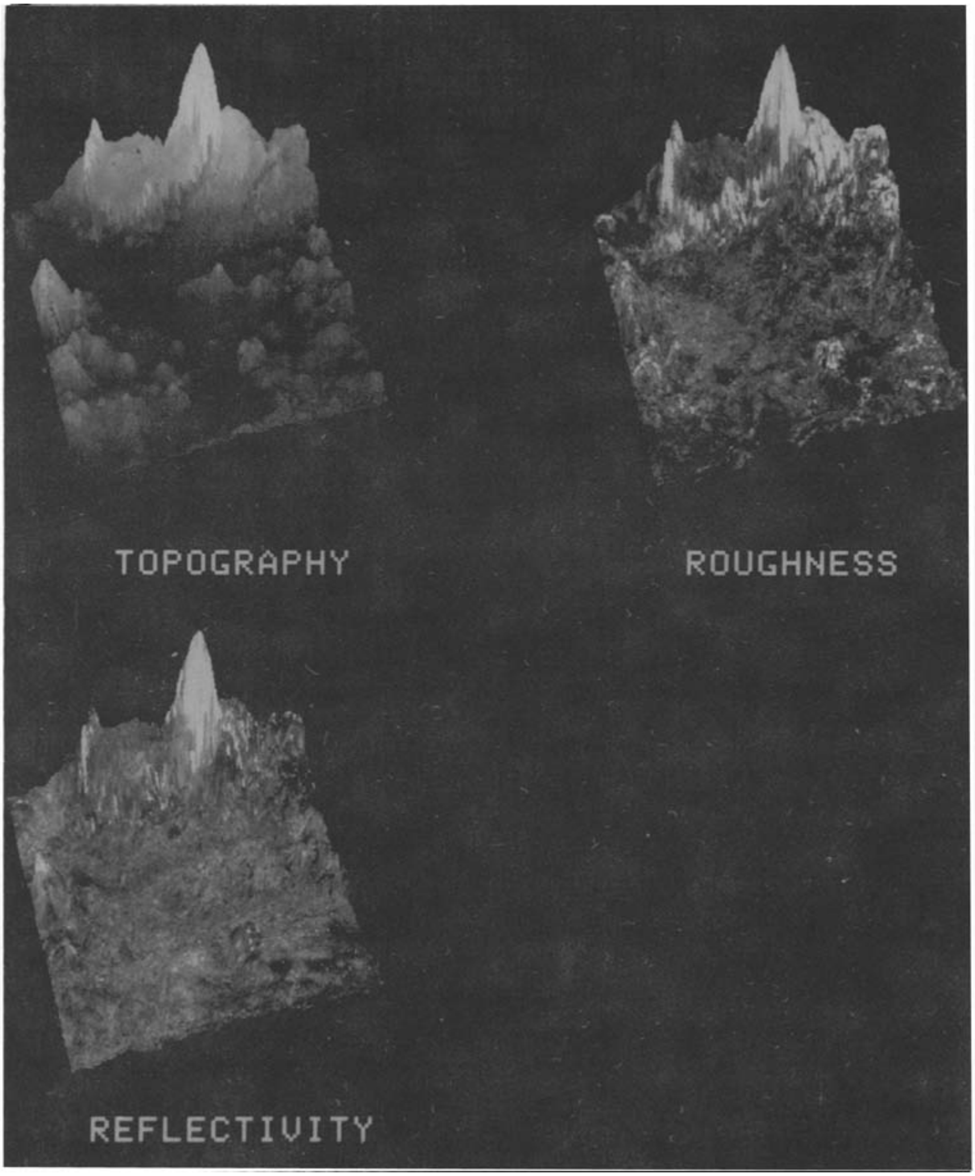
2.1. Nature of the Venusian Surface

View from Pioneer-Venus Radar System and Venera Landers

The Pioneer-Venus Radar Mapper Experiment produced data with beam footprint widths on the surface ranging from 30 to 100 km across, using a radar system that operated at 17 cm wavelength (Pettengill *et al.*, 1980). The observations were used to produce an elevation map covering about −80 to +80 degrees in latitude that shows continental-scale features separated by rolling plains, with 12 km of relief between the highest areas, such as Maxwell Montes, and lowland areas such as Atalanta Planitia. Figure la shows a perspective rendition of topography for the highlands Ishtar Terra, Beta Regio, and the surrounding rolling plains. Hypsometric plots extracted from the altimetry data show a single peak, corresponding to plains, and an asymmetrical tail corresponding to higher elevations. The lack of an Earthlike bimodal hypsometry suggests that the two planets have different mechanisms of crustal generation; i.e., Venus may not have generated large masses of low density continental crust. Rather, given the high correlation between topography and gravity, the venusian highlands may simply be sites of upwelling convection cells within the asthenosphere, although the nature of the crust and lithosphere, together with the tectonic style of Venus, are currently topics of considerable debate (Basilevsky *et al.*, 1986; Campbell *et al.*, 1984; Crumpler and Head, 1988; Head and Crumpler, 1987; Schaber, 1982; Kiefer and Hager, 1989).

The Pioneer-Venus (PV) Radar Experiment altimetry and side-looking mode imaging data have been used to estimate the quasi-specular and diffuse roughness of the surface and the Fresnel reflection coefficient (Ford and Pettengill, 1983; Pettengill *et al.*, 1982; Pettengill *et al.*, 1988). Figure 1b shows quasi-specular roughness (rms slopes) and Figure lc shows Fresnel reflection coefficient estimates derived from these data. The Hagfors (1964) model for quasi-specular scattering of microwave energy at small incidence angles was used to extract the estimates. Typical reflection coefficient values correspond to a relative permittivity of approximately 5.0, a value characteristic of dry rock. This result suggests that bedrock outcrops dominate the surface at the 30 to 100 km length scales sampled by the

a) b) c)



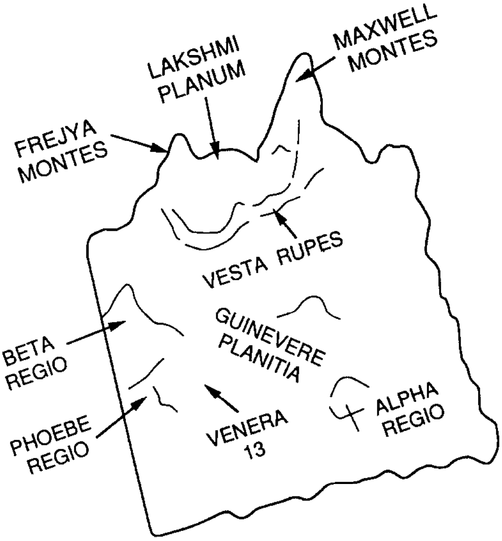


Fig. 1. Perspective views of topography (1a), radar rms slopes (1b-roughness), and radar reflectivity (1c) for the highlands of Ishtar Terra. Also shown is a sketch map of major features (1d). The views show elevations coded with brightness values for elevation, rms slope magnitude, and reflectivity, respectively. Note the high roughness and reflectivity values for Maxwell Montes (highest area shown) and the mountains surrounding Lakshmi Planum (central area). Lakshmi Planum is a smooth, elevated plateau with plains-like roughness and reflectivity. Data from Pettengill *et al.* (1988).

PV Radar Experiment, with no more than about 10 cm in thickness of soil cover. Head *et al.* (1985) and Davis *et al.* (1986) used PV reflection coefficient and rms-slope data to map radar geologic units and infer the physical properties of the surface, and noted that areas of relatively low reflectivity are more prominent near chasmata where fracturing would enhance weathering to produce fine material with low relative permittivities.

Topographically higher areas tend to have higher reflection coefficients, with the notable exception of the high plains area, Lakshmi Planum. The highlands generally also have higher rms slopes, both at the long length scales (greater wavelengths of radar) characteristic of quasi-specular scattering and at the shorter length scales (~wavelength) that control diffuse scattering. The highest values of relative permittivity are approximately 40, which suggest the presence of highly conducting materials such as iron sulfides, ilmenite, or magnetite (Pettengill *et al.*, 1982; Ford and Pettengill, 1983; Head *et al.*, 1985; Garvin *et al.*, 1985; Pettengill *et al.*, 1988).

The Soviet Venera and Vega landers provided data from the surface on the eastern flanks of Beta Regio (Figure 1) and on Aphrodite Terra. Soviet Venera images (Figure 2) of the surface show rock slabs, rock fragments several centimeters across, and crust-like soils, all of which could contribute sand and dust appropriate for aeolian activity (Florensky *et al.*, 1977a,b, 1983; Basilevsky *et al.*,

Fig. 2. Venera 13 image of the Venusian surface on the flanks of Beta Regio (see Figure 1d). Note the planar outcrops and darker soils with a platy appearance. Note also the disrupted nature of the soil adjacent to the lander.

1985). Soil elemental abundances were measured using x-ray fluorescence at the Venera 13, 14 and Vega 2 sites. The compositions are basaltic with the addition of 0.9 to 4.7% SO_3 (Surkov *et al.*, 1984, 1987). Rounded rocks show that the surface has been modified by weathering and erosion at the decimeter scale characteristic of Venera observations. Florensky *et al.* (1977a,b) assessed the Venera 9 and 10 images and suggested that mass wasting, perhaps aided by Venusian quakes, was responsible for the decimeter-scale weathering. Finer (i.e., centimeter-scale) weathering to round the edges of rocks was tentatively attributed to 'atmospheric action'. Garvin *et al.* (1981, 1984) analyzed the lander images and assessed the degree of weathering at the four sites. They noted that the soil to rock ratio decreases from the Veneras 9, 10 to 13, 14 sites, with Venera 14 consisting entirely of bedrock.

Pieters *et al.* (1986) analyzed the surface spectral reflectance at the Venera lander sites and noted that the surface appears generally dark in the visible part of the spectrum, with fine material being darker than rock outcrops. Beyond 0.7 μm the surface brightens, based on analysis of Venera 9, 10 photometer data, with near-infrared reflectances increased by a factor of 2 to 3 above the visible wavelength values. The increase was ascribed to the presence of ferric oxides. The presence of ferric oxide implies that the lower atmosphere is oxidizing, assuming that the surface is in thermodynamic equilibrium with the atmosphere, and that atmosphere-rock reactions have occurred.

Further evidence of fine particles on the Venusian surface and potential aeolian activity were discussed by Garvin (1981, 1984), who suggested that particles 18 to 30 μm in diameter were raised as dust clouds by the landers. Fine-grained material was also discussed by Selivanov *et al.* (1983) who analyzed Venera 13 and 14 images for dust in the atmosphere, and Kemurdzhian *et al.* (1983) and Avduevskii *et al.* (1983) who conducted experiments on the physical properties of the soils at the Venera 13 and 14 lander sites. In general, the lander observations are consistent with results obtained from the PV Radar Experiment if it is assumed that the observed soils are relatively thin (40 cm) and partly cover blocks and bedrock.

Surface as Viewed from Earth-based and Venera Radar Imaging

The Venera 15 and 16 orbiters mapped about 30% of the venusian surface using 8 cm wavelength radar with an incidence angle of about 10° and a resolution of several kilometers (Barsukov *et al.*, 1986). Data were acquired from the north pole to approximately 30° north latitude. Images show a planet dominated by volcanic and tectonic features at Venera resolution, as evidenced by numerous volcanoes, volcanotectonic depressions, and lava flows in the rolling plains that occupy 70% of the area mapped (Barsukov *et al.*, 1986). In addition, the Soviets identified a unit termed *ridge-and-band plains*, consisting of numerous narrow ridges, presumably of tectonic origin. *Parquet* or *tessarae terrain* consists of intersecting ridges and grooves and appears to be regions subjected to complex, repeated deformation. Bindschadler and Head (1988, 1989) found that tessarae

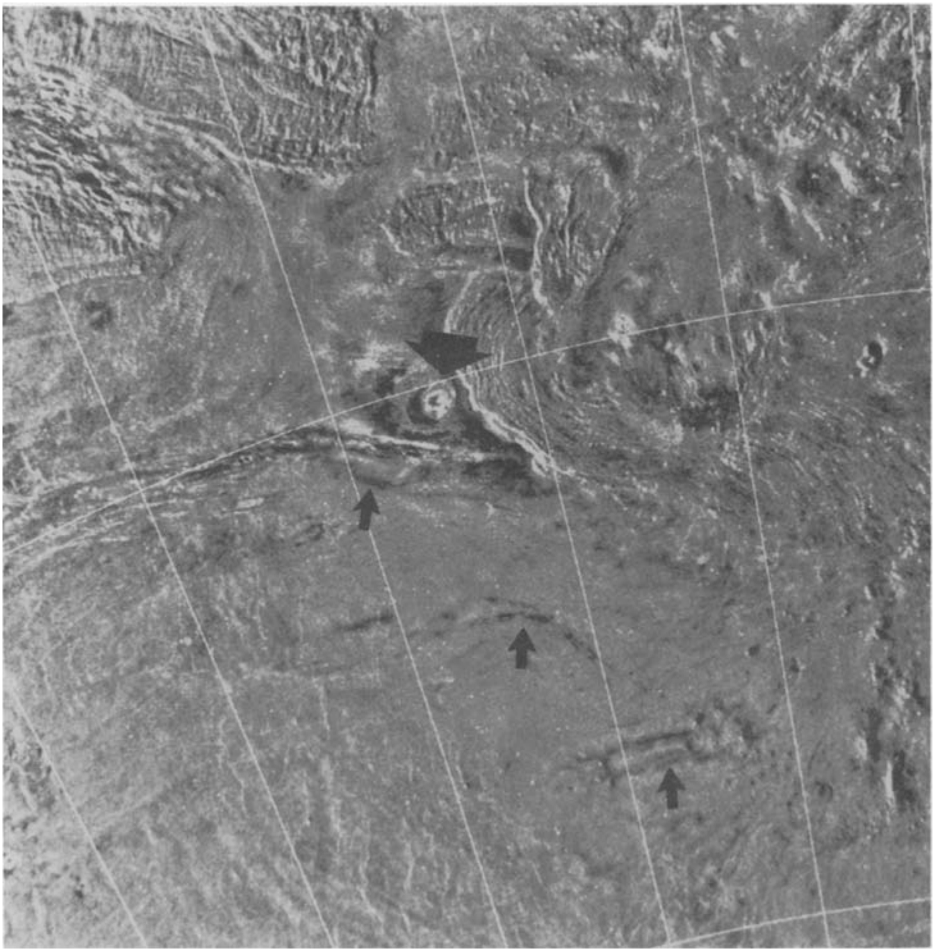


Fig. 3. Portion of Venera quadrangle B6 radar image mosaic showing regions of low radar backscatter (arrows) interpreted to be aeolian deposits by Barsukov *et al.* (1986). Also shown is an impact crater (wide arrow). Approximate location 95° to 115° E, 67° to 74° N.

correspond to regions with high rms slopes and low reflection coefficient values in PV radar data. They ascribed this observation to intense fracturing to produce roughness and soils shed from steep slopes. In fact, the Pettengill *et al.* (1988) locations where 5% of the planet is covered with 'radar-deep' soils coincide with locations of tessarae for areas where the Soviet and PV data overlap. Another unit was termed *subparallel ridge and groove terrain*, which surrounds Lakshmi Planum. Venera views of the northern part of Beta Regio show subparallel rifts that represent the northern extensions of the uplifted, rifted terrain detected in Arecibo data (Stofan *et al.*, 1989). Although more than one hundred impact craters (some with radar bright ejecta deposits) have been identified, the frequency is lower than on the Moon (Ivanov *et al.*, 1986; Basilevsky *et al.*, 1987). Thus, the overall appearance of the venusian surface suggests extensive and relatively recent volcanism and tectonism, although it would be difficult to detect erosional or depositional features at the spatial resolution that pertains to Venera radar observations (Arvidson *et al.*, 1988). On the other hand, Barsukov *et al.* (1986) suggest that east-west trending radar dark features (Figure 3) to the northeast of Ishtar Terra are wind related and indicate surficial processes.

Most Earthbased radar observations have been made by the Arecibo and Goldstone radiotelescopes and are limited to ~25% of the surface centered around the equator and prime meridian (e.g., Rumsey *et al.*, 1974; Goldstein *et al.*, 1978; Campbell and Burns, 1980). Data from the Arecibo Observatory (12.5 cm wavelength radar) cover large regions with fairly high incidence angles (in which diffuse scattering dominates the radar echo) and show that Beta Regio is rifted, has volcanoes, and is rough at radar wavelength scales. Alpha Regio is suggestive of tessarae terrain and the plains are shown to have variable roughness. Goldstone observations are acquired at incidence angles of $\leq 10°$ and largely cover the Guinevere Planitia area (Arvidson *et al.*, 1990). Goldstone data show the same distribution of plains features as seen in the Venera data for the region to the north. Recent, calibrated Goldstone data have allowed separation of reflection coefficients and rms slopes. Some surfaces, including volcanic plains, have materials with high relative permittivities, even at low elevations (Jurgens *et al.*, 1988).

2.2. Constraints on the Nature and Rates of Resurfacing Processes

In this section we examine photogeological, thermodynamic, and kinetic analyses to constrain the nature and rates of resurfacing of Venus. Analysis of crater morphologies shows a range of preservation states from features with obvious impact morphologies to 'ghost' craters (Ivanov *et al.*, 1986; Basilevsky *et al.*, 1987), suggesting that Venus has continued to be resurfaced by some process(es). Figure 4 shows various resurfacing scenarios for Venus, including constant rates of crater obliteration, 'spikes' in the obliteration rate, and accumulation of a production population. The methodology used to model crater production and obliteration is similar to the one described in Plaut *et al.* (1988). A lunar cratering rate is adopted in which craters are assumed to form according to a log-log linear power law with a slope of -2, and crater lifetimes are assumed to be proportional to crater depths. Figure 4 includes two crater populations: (a) the subset of craters defined to be of impact origin by Ivanov *et al.* (1986) and Basilevsky *et al.* (1987) and (b) the total population of craters, including vague circular features mapped by these authors. Note that the total population has about three times the number of craters than the population of obvious impact craters.

It is difficult to determine which of the models shown in Figure 4 is appropriate for Venus because: (a) crater 'relaxation' is not included (e.g., Cordell, 1981; Solomon *et al.*, 1982); and (b) the production of small (<20 km; Ivanov *et al.*, 1986) craters is deficient due to atmospheric shielding. However, it would appear

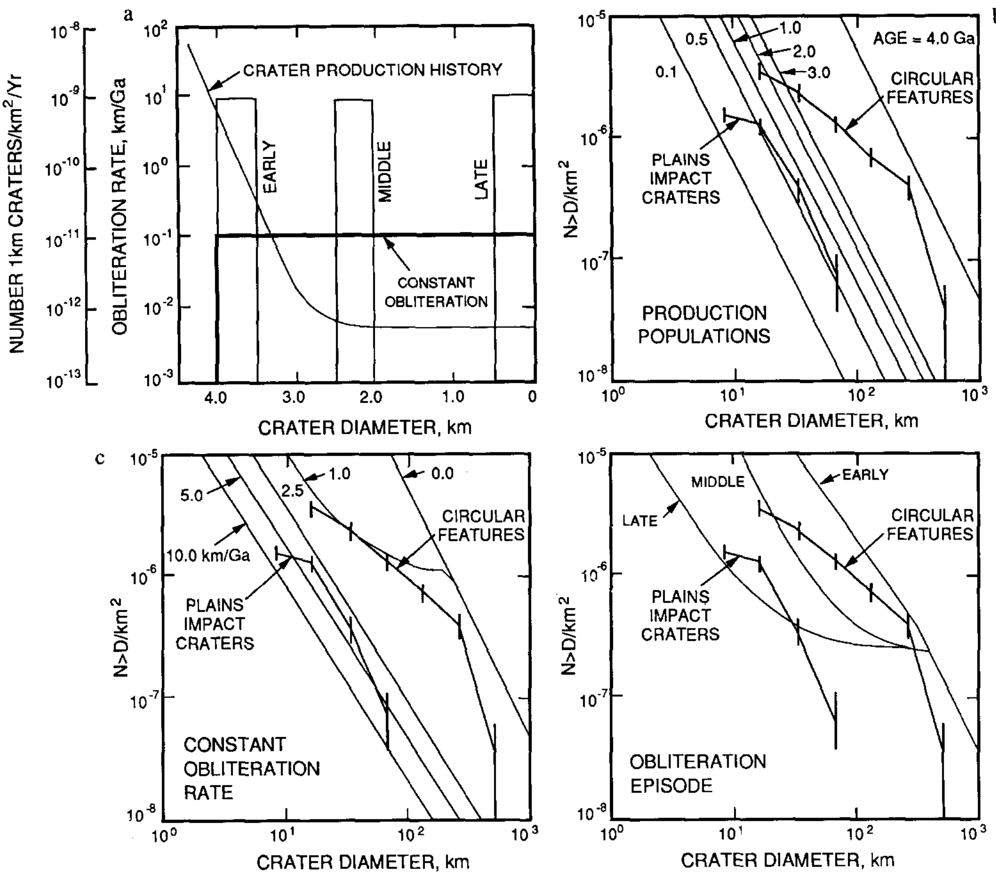


Fig. 4. Series of graphs depicting alternate resurfacing histories for Venus. Figure 4a shows assumed cratering rate and obliteration rate histories. Figure 4b shows model crater size-frequency distributions assuming no obliteration, i.e., only crater production occurs. Figure 4c shows results for various steady state obliteration rates. Figure 4d shows size frequency distributions resulting from spikes in obliteration rates in early, middle, and late geologic time. Data for putative impact craters and all circular features derived from Venera 15 and 16 data (Basilevsky *et al.*, 1987) are also shown.

that craters of obvious impact origins ⩾20 km in diameter are either in production with an age of several hundred million years or in steady state between production at the lunar cratering rate and obliteration at a rate of perhaps 2 to 4 km/Ga. The production age is similar to the value quoted by Schaber *et al.* (1987) and the obliteration rates are comparable to those found by Arvidson and Plaut (1988) and Grimm and Solomon (1987), respectively. The obliteration rate must be considered an upper bound because only obvious impact craters are utilized. If it is assumed that the total population of craters is of impact origin, then the rate of obliteration would be lower by about a factor of three. The addition of relaxation would lower the value even further. Thus, we conclude that some set of steady state processes resurface the planet at values up to 2 to 4 km/Ga.

Cutts *et al.* (1981) noted the occurrence of bright ring craters on Venus in Earth-based radar images and suggested that the rings correspond to rough, fresh ejecta deposits. Thompson *et al.* (1986) assessed Earth-based radar cross-sections of large craters on Venus and suggested that the rough rims and ejecta may be traps for windblown sediments, thereby explaining the presence of bright ring craters and other craters without bright rings. The rings disappear with time either because of erosion or burial and smoothing by aeolian deposition. Ivanov *et al.* (1986) noted that about 25% of the impact craters seen on Venera 15 and 16 data have radar bright haloes associated with ejecta deposits and ascribed the appearance to increased roughness. Assuming a steady rate of weathering and erosion, a surface age of 0.5 to 1.0 Ga, and the fact that only 25% of the craters possess the haloes, they suggested that 125 to 250 Ma are required for the roughness to be degraded to the point where the haloes would not be discernible in Venera 15, 16 data. If decimeter roughness is involved, then the removal rate is about 10^{-2} km/Ga, implying that weathering and erosion are trivial components of the planet's resurfacing processes.

On the other hand, theoretical considerations suggest a higher rate of weathering and erosion than derived from the inferred rate of crater halo disappearance. Nozette and Lewis (1982) show that chemical reactions vary with altitude on Venus and, in particular, Maxwell Montes and other high terrains should have atmosphere-surface interactions dominated by production of carbonates, sulfates, and sulfides from reactions between atmospheric CO_2 and SO_2 and surface material. They further suggest that the weathered material is subsequently transported by winds to the plains, where CO_2 and SO_2 are liberated during re-equilibration to new atmospheric temperatures and pressures. Fegley and Prinn (1989) conducted experiments to determine the rate of one of the possible reactions, the production of anhydrite by reaction of calcite and SO_2. The estimated rate is the equivalent of 1 km/Ga of anhydrite production, a value that would be a significant fraction of the upper limit of 2 to 4 km/Ga for the total resurfacing rate of Venus. Thus, an alternative to a Venus dominated by volcanism and tectonism is one in which both endogenic and exogenic processes have played significant roles in shaping the surface.

2.3. The atmosphere

Aeolian processes involve the interaction of the atmosphere and the lithosphere. Although Earth-based observations provided important clues to the characteristics of the Venusian atmosphere (reviewed by Dollfus, 1975), global circulation patterns for the upper atmosphere were defined from images taken in the visible and near-ultraviolet during the Mariner 10 encounter in 1974 (Murray *et al.*, 1974). Analysis of Pioneer-Venus data shows that wind flow is easterly at altitudes of 10 to 80 km, with velocities of up to 100 m/s at the equator (Counselman *et al.*, 1979). As reviewed by Schubert (1983) and Saunders (1987), the upper rotation of the atmosphere is driven primarily by temperature differences between the equator and the poles, and is partly maintained by thermal tides.

Information on atmospheric circulation was also provided by the Vega mission, during which two balloons were inserted near the equator and were observed to drift in an easterly direction (Blamont *et al.*, 1986). Results from the balloons show that topography on Venus may influence atmospheric circulation patterns because vertical wind speed variation was greater for the balloon that drifted over the equatorial highland, Aphrodite Terrae (Young *et al.*, 1987). Dobrovolskis and Saunders (1986) concluded that slope winds would dominate the movement of windblown material and that the general patterns of wind erosion and deposition would be governed by topography.

Although few measurements of the wind at the surface have been made, some data relevant to aeolian processes have been obtained. Venera landers 9 and 10 measured wind speeds of 0.5 to 1 m/s (Florensky *et al.*, 1977b; Ksanfomality *et al.*, 1983) at the height of the wind sensors (~1 m above the surface). More recent measurements of wind speeds obtained by the Pioneer-Venus atmospheric probe indicate a surface wind speed of 1 to 2 m/s (Counselman *et al.*, 1979). Although it is difficult to convert either of these measurements to surface wind friction speeds (u_*, the parameter required to assess the potential for aeolian activity) without detailed knowledge of the wind speed profile and surface roughness, these values are well within the range predicted as necessary for particle movement (Greeley *et al.*, 1984a).

Finally, we note that atmospheric pressure and temperature vary greatly on Venus. At the top of Maxwell Montes the pressure is ~40 bars and temperature is ~650 K, while the low plains are subject to pressures of ~107 bars and temperatures of ~757 K (Seiff, 1983). Presumably, wind velocities increase with elevation. The large variation in atmospheric conditions with elevation suggests that altitude may be a strong modulator of aeolian processes.

3. Physics of Windblown Particles on Venus

The entrainment of sand and dust by wind has long been of interest on Earth. Bagnold (1941) conducted wind tunnel experiments to study the physics of windblown sand and set the stage for subsequent laboratory simulations. His approach was adapted to study aeolian processes in other planetary environments (primarily Mars and Venus), as reviewed by Greeley and Iversen (1985). In this section we consider the requirements to move particles by wind on Venus (i.e., threshold conditions), infer the flux and speed of windblown grains, explore possible bedforms such as ripples and dunes that may form under venusian conditions, and consider weathering processes induced by aeolian transport.

3.1. Particle Threshold

Bagnold (1941) described three modes of aeolian transport on Earth: surface creep, saltation, and suspension (Figure 5). Generally, surface creep involves very

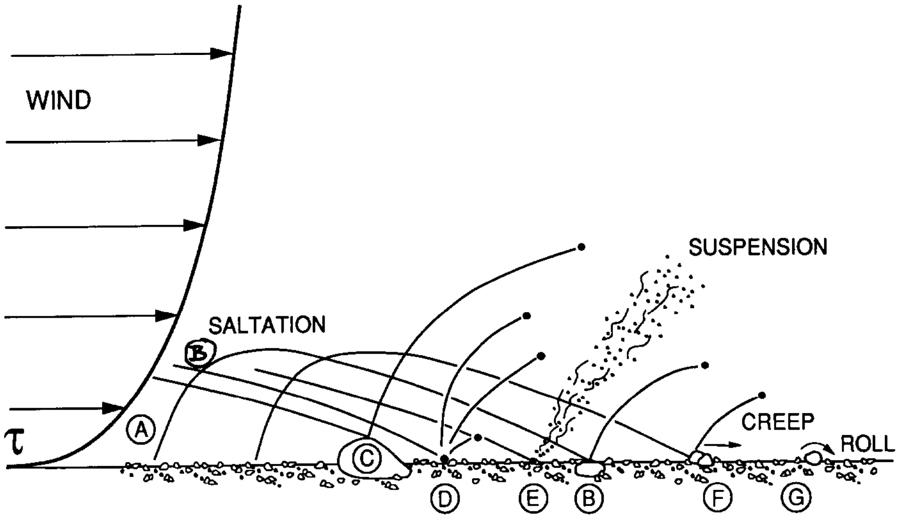


Fig. 5. Diagram showing the four principal modes of aeolian transport of grains on Venus: surface shear stress (τ) exerted by the wind causes grain (A) to lift off the surface, carries it downwind back to the surface where it bounces (B) back into flight; this motion is termed *saltation*; grain at (C) hits a large rock – possibly causes some erosion – and elastically rebounds to a relatively high saltation trajectory; grain at (D) strikes the surface and 'triggers' other grains into saltation; grain at (E) strikes the surface containing very fine particles (too fine to be moved by the wind alone in this case; see threshold curve Figure 6) and sprays them into the wind where they are carried by turbulence in *suspension*; grain at (F) strikes larger grain and pushes it downwind a short distance in a mode of transport termed *impact creep*, or *traction*; wind alone may also *roll* (G) some grains across the surface.

coarse grains (2,000 to 4,000 μm), saltation involves sand grains (~40–2,000 μm), and suspension involves fine particles (<40 μm). Because fine-to-medium sand is the size (~100 μm) most easily moved by the wind (that is, by weakest winds), on Earth most near-surface windblown particles are moved by saltation. On Earth both surface creep (called 'impact creep' by Sharp, 1963) and suspension result primarily from the impact of saltating grains. Except for an additional mode of transport (described below), the same is true on Venus.

Saltation threshold wind speed (designated u_{*t}, the minimum wind speed necessary to initiate saltation) is the fundamental parameter governing most aeolian processes. Saltation threshold has been analyzed for terrestrial conditions (Bagnold, 1941; Chepil, 1945; and others) and for Mars (Sagan and Pollack, 1969; Greeley *et al.*, 1976, 1980; Iversen *et al.*, 1976). Theoretical predictions of Venusian threshold have been made by several investigators (Sagan, 1975; Hess, 1975; Iversen *et al.*, 1976; Iversen and White, 1982), who show that threshold is a function of grain size and density, gravitational acceleration, and atmospheric temperature and density.

Experiments have been run under simulated Venusian conditions to validate and constrain theoretical predictions. The Venus Wind Tunnel (VWT) was fabricated to study aspects of particle motion under simulated venusian conditions (Greeley *et al.*, 1984a). Experiments were performed to determine saltation threshold for particles ranging in size from 30 to 650 μm and results (Figure 6) were compared with theory. In contrast to the prediction of Hess (1975) who suggested that the particle size most easily moved would be 32 to 34 μm in diameter, experiments showed that the most easily moved particles are ~75 μm in diameter. As on Earth and Mars, both smaller and larger particles are more difficult to entrain than fine sand on Venus.

Experiments have also been conducted to assess modes of aeolian transport (e.g., saltation) on Venus. Greeley and Marshall (1985) ran six sizes of well-sorted particles ranging in size from fine sand to small pebbles (105 to 13,000 μm). Three types of particle motion were noted: (a) wobbling, (b) rolling, and (c) fully

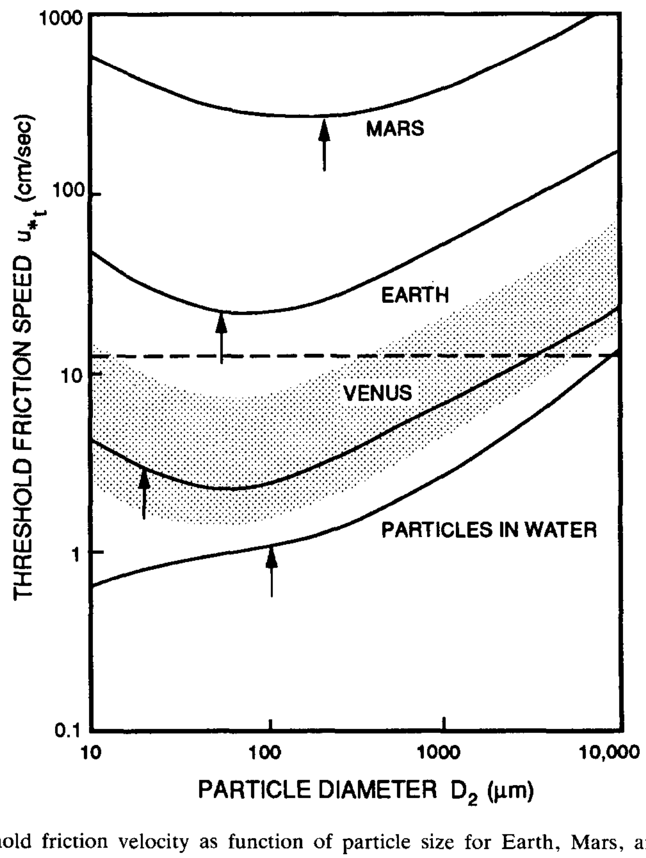


Fig. 6. Threshold friction velocity as function of particle size for Earth, Mars, and Venus in air, compared with threshold in water on Earth; arrow indicates the transition between suspension threshold for small grains to saltation threshold for larger grains. Shaded zone gives range for Venus from the lowest elevations (lowest threshold) to the highest elevations; dashed line corresponds to highest wind velocity measured at the Venera landing sites (from Iversen *et al.*, 1976 and Greeley *et al.*, 1984a).

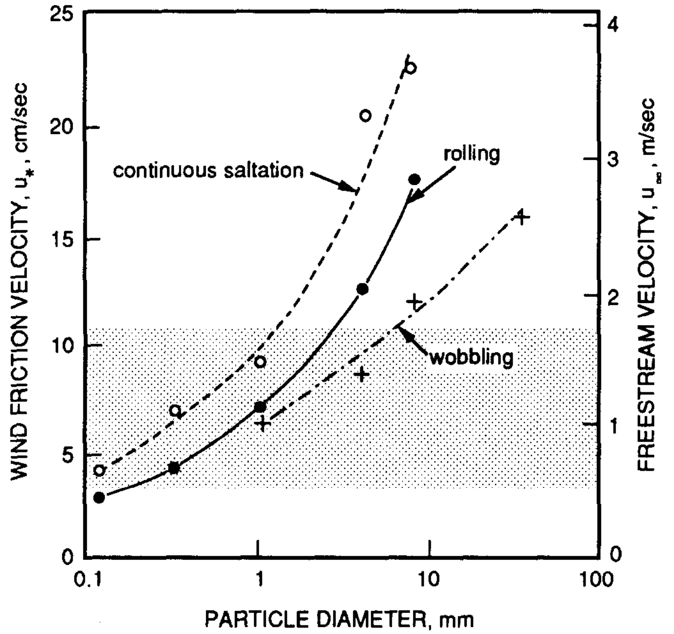


Fig. 7. Results from threshold tests in the Venus Wind Tunnel showing the lower wind friction velocity for transport by rolling than for continuous saltation; shaded area shows wind velocity inferred for the Venera landing sites, as derived from measurements of the near-surface winds (from Greeley and Marshall, 1985).

developed saltation (Figure 7). It was inferred that suspension of fine grains and impact creep of very coarse grains would also occur on Venus. In wobbling motion, the grains quivered but did not move out of place. At a slightly higher wind speed, the grains began to tumble along the surface in a rolling mode and only a few grains would saltate. Continuous (fully developed) saltation did not occur until markedly higher wind speeds were available. The values shown on Figure 7 for continuous saltation correspond to the single threshold curves predicted for Venus in Figure 6. Thus, when the rolling mode of wind transport is taken into account, minimum wind speeds on Venus for aeolian activity may be 30% less than previous estimates which were based solely on saltation threshold, a result which suggests that aeolian activity would be more frequent than previously suspected.

The rolling mode of transport observed in VWT did not lead to a cascading effect, which on Earth ordinarily transforms the surface of the bed rather suddenly into a saltation cloud. Observations show that the rolling mode can be maintained in VWT for an indefinite period. Thus, Venusian aeolian transport differs significantly from that on Earth and, in some respects, the movement of particles resembles that of water-driven particles on Earth. Bagnold compared particle movement in air with particle movement in water on Earth and noted that the fluid/particle density ratio is 1:2,000 in air and 1:2.65 in water; in the dense

Venusian atmosphere this ratio is approximately 1:40 (Iversen *et al.*, 1987). Thus, aeolian conditions on Venus may share characteristics of both aeolian conditions on Venus and aqueous conditions on Earth, and may lead to the formation of unusual bedforms, discussed below.

3.2. Flux of aeolian particles

First assessed by Bagnold (1941), the flux of windblown grains on Earth has been analyzed by many investigators (Kawamura, 1951; Horikawa and Shen, 1960; Belly, 1964; Williams, 1964; White, 1979; Willetts, 1983; and others). An expression for saltation flux was derived from theory and experiments by Kawamura (1951) and was shown to apply to both terrestrial and Martian environments by White (1979) as

$$Q = 2.61 \frac{\rho_a}{g} (u_* - u_{*t})(u_* + u_{*t})^2 , \quad (1)$$

where Q = saltation flux (in g/cm · s), ρ_a = atmospheric density, and g = acceleration due to gravity. The constant, 2.61, was determined in wind tunnel tests for subrounded quartz sand 100 μm in diameter. However, a different constant may be required for different material, as Q is known to vary with particle shape and size distribution (Williams, 1964) and particle density (Greeley *et al.*, 1980). To assess this expression for Venus, saltation flux was determined using VWT (Greeley *et al.*, 1984a; Williams and Greeley, 1985) in which a given mass of sand was spread over the test plate and the tunnel was run at a given wind speed and duration. The amount of sand remaining on the test plate was recovered and the mass was determined. The total flux, Q, was then derived as the amount of sand removed from the plate divided by the plate width and wind duration. Results agree closely with the theoretical prediction for fine (75–90 μm) quartz particles (Figure 8). However, there was a systematic discrepancy between experimental results and predictions for coarse particles (500–600 μm). This was explained by Williams and Greeley (1987) who showed that the high fluid density of the Venusian atmosphere entrains a large mass of particles, but reaches a critical stage in which the flux is effectively ‘choked’ as the fluid becomes saturated with grains. If we assume a steady supply of sand-size particles, the flux of particles could be as high as 2.5×10^{-5} g/cm/s, based on the calculations by Williams and Greeley (1985, 1987).

3.3. Particle speed

Relatively little research has been carried out regarding the speed of windblown grains as a function of wind speed, even for terrestrial conditions (Willetts, 1983). Yet, in order to assess potential abrasion of rocks and erosion of landforms it is essential that particle speeds be known as a function of wind speed and height above the surface. Experiments have been run in VWT to obtain appropriate data (Greeley *et al.*, 1983; White, 1986). The approach was to photograph particles in flight using high speed motion pictures and to analyze the trajectories of individual

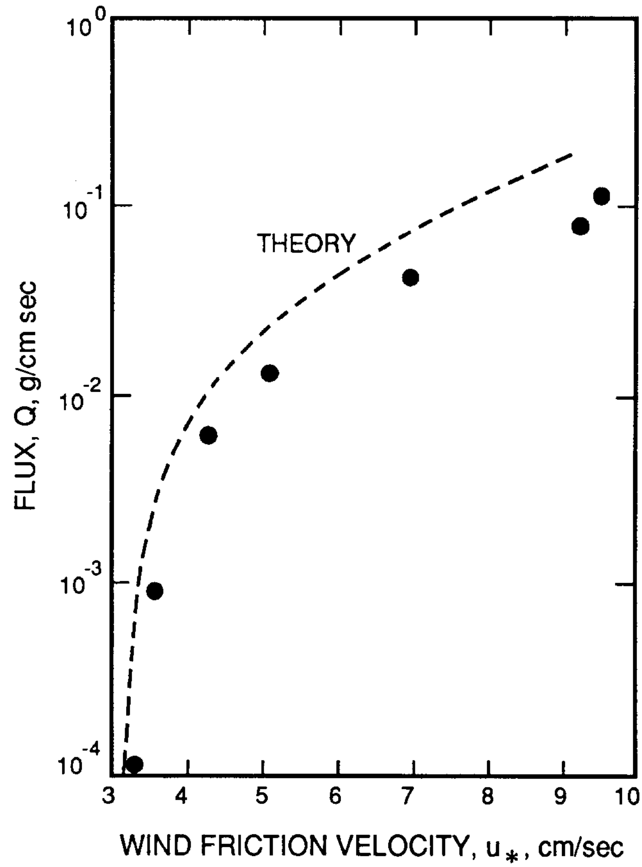


Fig. 8. Venus Wind Tunnel results for flux (Q) of quartz particles 75 to 90 μm in diameter as a function of surface shear stress, u_*, compared to theory. The lower flux obtained in experiments is attributed to 'choking' of flow, which is not taken into account by theory; wind friction velocities shown are appropriate for those measured at the Venera landing sites (from Greeley *et al.*, 1984a).

grains. Figure 9 shows results for 500–600 μm quartz particles subjected to a wind of 3.62 m/s ($u_* = 0.2$ m/s). Particle speeds are given both in meters per second and as a percentage of freestream wind speed (u_∞). This latter function is useful in normalizing data for comparisons of different particle sizes and wind speeds, and for comparison with other planetary environments. In general, it was found that particle speed increased with height above the surface; not only is the wind speed greater with height, but also the particles are accelerated to a greater speed than those at lower heights simply because they are in flight for a longer time.

An analysis of velocities for particles on different parts of their saltation trajectories shows that particle velocity increases in the early part of the trajectory, as predicted by White (1981). However, experiments showed that many particles decelerate during the falling part of the trajectory rather than steadily accelerating as is the case on Earth and Mars. Although data are limited, this result was

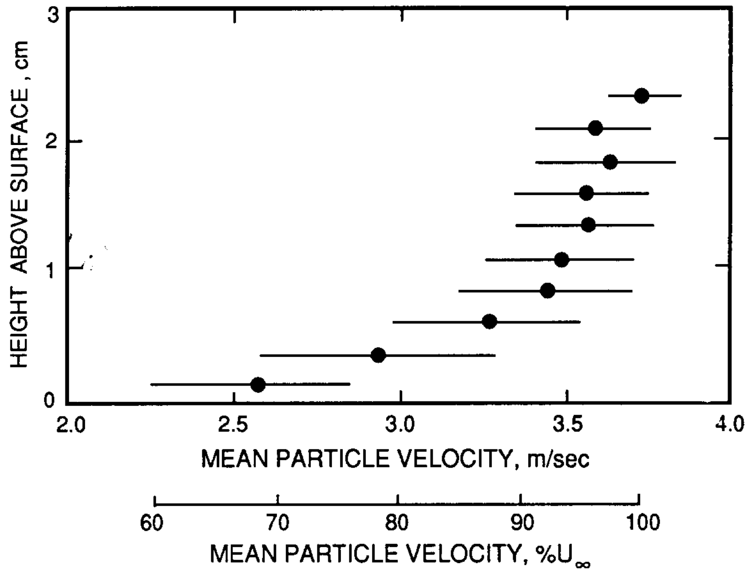


Fig. 9. Velocities of 500- to 600-μm-diameter quartz particles subjected to a freestream wind speed of 3.62 m/s (wind friction velocity = 0.2 m/s) in venusian simulation (from Greeley *et al.*, 1983).

attributed to efficient fluid-particle coupling; as a particle descends through the atmospheric boundary layer, it encounters progressively slower wind speeds and an accompanying retardation of motion. Although similar retardation of motion may occur on Earth and Mars (Figure 10), the greatly increased atmospheric density on Venus makes the effect much more pronounced. Knowledge of particle

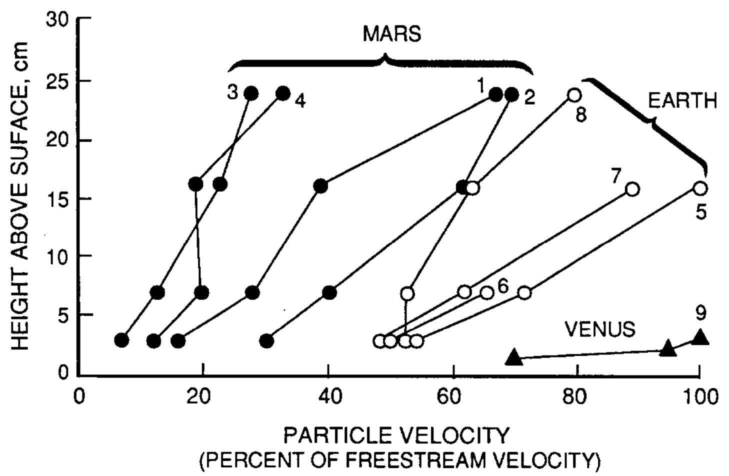


Fig. 10. Comparison of particle velocities on Earth, Mars, and Venus. In general, grains achieve a much higher velocity (in relation to wind speed) under Venusian conditions than on Earth and Mars (from Greeley *et al.*, 1983).

velocities enable better estimates of physical weathering and erosion on Venus, as discussed below.

3.4 Bedforms

Potential aeolian bedforms on Venus have received relatively little attention, although the Soviets had predicted a miniature type of dune, termed *microdunes* (Florensky *et al.*, 1983). In addition, White (1981) suggested that ripples on Venus may be relatively short (a few centimeters) owing to the relatively short path lengths of saltating particles.

Bedforms were produced in VWT by Greeley *et al.* (1984b) and Bougan and Greeley (1985) as a function of particle size and wind speed (Figure 11). From these experiments, three flow regimes (1, 2, and 3) were identified, based on threshold wind speeds for rolling/intermittent saltation, continuous saltation, and suspension. Regime 1 is characterized by longitudinal bedforms, Regime 2 has transverse bedforms, and Regime 3 has flat (featureless) beds. Bedforms produced in Regime 1 were generally parallel to the wind and were predominantly longitudinal furrows and ridges, but also included 'chaotic topography' and chevron-shaped features. These bedforms were typically restricted to particles <100 μm, resulted mostly from erosion of loose sediments, and occurred at sub-saltation wind speeds. Bedforms in Regime 2 were transverse to the wind, regularly spaced, and occurred

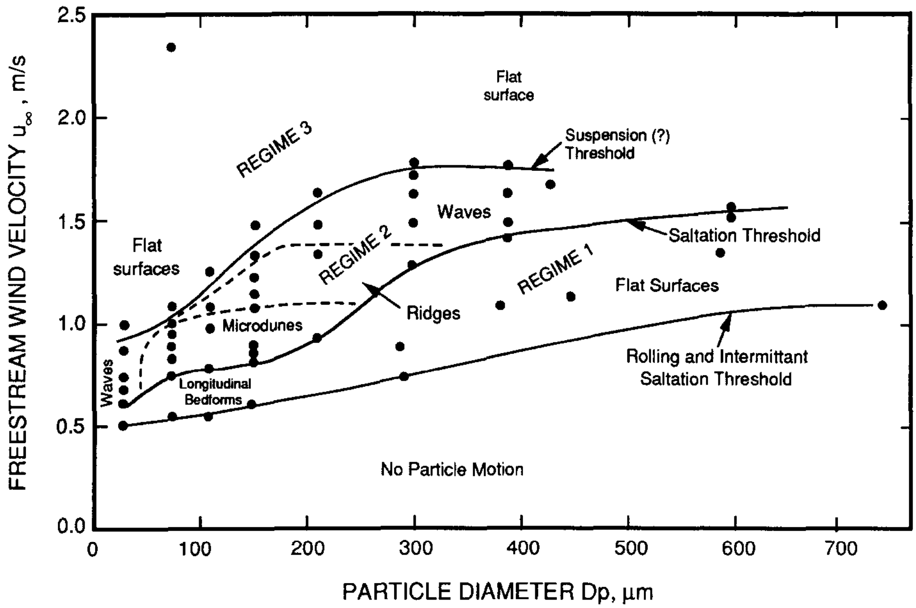


Fig. 11. Bedform regimes as a function of freestream wind speed and particle size and Venusian conditions; freestream wind velocity range shown is appropriate for winds measured at the Venera landing sites (from Bougan and Greeley, 1985).

at wind speeds 0.7 to 1.8 m/s. Their wavelengths were 10 to 15 cm and their heights were <1 cm. At the lowest wind speeds asymmetric 'microdunes' with well-defined slip faces formed (Figure 12), whereas symmetrical waves with no slip faces formed at the highest wind speeds. Ridges transitional between microdunes and waves occurred between speeds of 1.1 and 1.4 m/s. Ridges and waves also formed in sand ~250 μm in diameter, the upper particle-size limit for microdune development. Ridges graded imperceptibly into both bedform types, suggesting that all transverse bedforms may be part of a morphological continuum. In Regime 3 the bed was generally flat. The transition from Regime 2 to Regime 3 occurred over a relatively narrow range of wind speeds (within ~0.1 m/s) and was characterized by degradation of microdunes into ridges, then waves, with an overall increase in wavelength. The size of the microdunes and the length of the longitudinal grooves may increase with time and sand supply on Venus. Although such growth cannot be tested in VWT because of the limited size of the chamber, there is nothing inherent in the processes of formation to retard their size.

Fig. 12. Microdune produced in the Venus Wind Tunnel, showing steeply dipping cross-beds; note that the strata are parallel to the slip face of the dune (area shown is about 10 cm wide; wind is from the left; from Greeley *et al.*, 1984b).

3.5. Weathering

Windblown particles have the potential for physically weathering surface materials on Venus through impact and abrasion. Weathered surface debris will be redistributed and fresh, chemically reactive surfaces will be exposed. The Venus Simulator (Greeley *et al.*, 1987) was constructed to investigate potential aeolian weathering on Venus. It is capable of achieving temperatures up to ~800 K and pressures up to 114 bar and can mobilize particles to simulate rolling or saltation of material, either in free motion or as impacts against rock surfaces. Tests were conducted at six pressures (12 to 95 bars) with the temperature held constant at 737 K. In addition, tests were conducted at 47 bars/660 K and 105 bars/750 K – conditions representative of the highest and lowest elevations on Venus, respectively (Marshall *et al.*, 1988).

In initial experiments, target rocks were subjected to 10^5 impacts by particles at a velocity of 0.5 to 0.7 m/s, appropriate for the low winds on Venus. This is equivalent to travelling about 3 km on Venus, a relatively short distance for aeolian transport. In later experiments, the number of impacts was reduced to $2 \cdot 10^4$. Most tests were conducted with basalt targets and basalt particles, which is consistent with the detection of rocks of (apparent) basaltic composition on Venus (Surkov *et al.*, 1984, 1987). Figure 13 shows results from the experiments. Despite the very low impact velocities, the edges of all the colliding grains became rounded. Material was removed by chipping to produce pits, and by finer-scale abrasion that led to smoothing of areas between the pits. Average attrition was estimated from analysis of scanning electron microscope images ≤1% volume reduction of the grains for the 14-hour experiments. An assumption wind frequency of 5% for saltation-strength winds gives a lifetime of less than 10^3 years for a sand-size grain on Venus. Experiments showed that the rate of abrasion was apparently unaffected by temperature or pressure for the ranges tested.

Profiles of the rock targets impacted by grains before and after each test showed an increase in height of the weathered surface of several micrometers. Both the surface appearance and the increase in elevation are attributed to accretion of comminuted material derived from the incident grains. Although the experiments did not show abrasion of the target surface by the incident grains, the current design for the rock target placement in the chamber exposes only a flat surface to impact. It is likely that abrasion of target edges would occur at a rate similar to the abrasion of edges on the impacting grains, if they were exposed. Thus, angular projections on rocks and bedrock surfaces on Venus would probably be abraded, even in gentle winds, as suggested by Garvin (1984).

Ventifacts (wind-sculpted rocks) may have a different appearance on Venus in comparison to ventifacts on Earth. On Earth, rocks are commonly undercut at a height of 15 to 20 cm above the surface. The height represents the maximum kinetic energy of impacting windblown grains considering the increase in particle velocity with height above the surface and the decrease in flux with height. Because

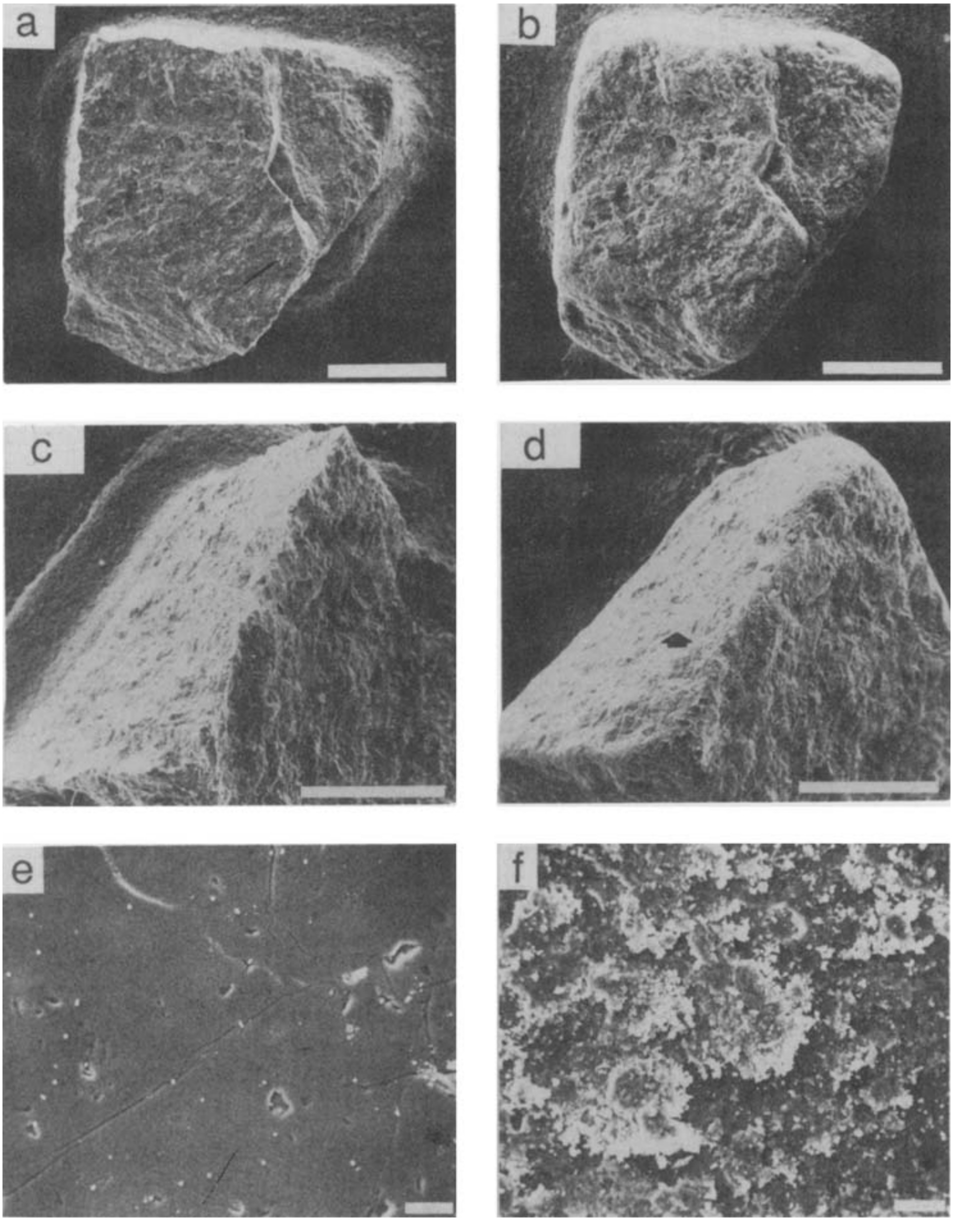


Fig. 13. Results from mechanical weathering experiments conducted in Venusian simulations (from Greeley *et al.*, 1987; and Marshall *et al.*, 1988); 3 mm basalt grain used as impactor before (a) and after (b) the experiments (conducted at 40 bars, CO_2 gas, 737 K) showing that the corners and edges of the grain have been eroded, even at the low (0.6 m/s) impact velocities; experiment was run for 10^5 impacts, the equivalent of a grain travelling about 3 km distance in 14 hours; (c) detail of grain edge before and (d) after experiment showing erosion of edges, but little modification of the 'faces' (arrow) of the grain; (e) rock (basalt) target shielded from impact for comparison with part of target (f) subjected to impact by grain shown in (a) and (b) and the accretion on the target of comminuted debris from the grain; scale bars on (a,b,c,d) = 1 mm; on (e,f) = 10 μm.

the saltation trajectories are lower on Venus (White, 1981), the height of maximum abrasion may be only a cm above the surface. This may explain the lack of earth-like ventifacts in Venera images of the surface (e.g., Figure 2).

4. Discussion

MAGELLAN will, beginning in late summer 1990, return radar images with approximately 150 m radar resolution, calibrated to differential radar cross-section with 5 dB accuracy, over most of the surface. The altimetry portion of the radar system will have a 10 km footprint. In addition, during the extended missions, multiple incidence angle data will be acquired over given areas. The reader is referred to Saunders *et al.* (1990) for more details, although it should be clear that the order of magnitude increase in resolution as compared to existing data, the calibrated nature of the data, and the variety of coverage will significantly increase our understanding of the nature of the venusian surface. Specifically, MAGELLAN data will provide detailed views of surface morphology, estimates of elevation, and the ability to separate reflection coefficients from roughness, that cannot be determined from existing data.

From this review, there appear to be two competing hypotheses on the role that aeolian and other surficial processes play in the modification of the venusian surface. On the one hand, there should be an abundant supply of loose material on the surface and winds of sufficient strength to redistribute them, forming clastic sedimentary deposits. Moreover, reactions between the atmosphere and lithosphere should proceed at a rate to generate extensive chemical sedimentary deposits, such as anhydrite. On the other hand, radar data suggest little in the way of sedimentary materials for most of the surface of the planet that has been observed. Moreover, rates of resurfacing inferred from degradation of bright-halo impact craters suggest that mantling by windblown and other surficial material is trivial. We now return to the questions raised in the introduction to this paper, focus on these competing ideas, and suggest observations that could be made via Magellan to constrain the hypotheses.

What is the Nature of Particle Movement by Wind on Venus?

Experiments and theoretical considerations show that under present conditions, parts of Venus could be subjected to aeolian processes at rates comparable to some desert regions on Earth. However, because of the high atmospheric density, particles entrained by the wind would travel at speeds ~1/10 those on Earth. Nonetheless, the grains could cause chemical and physical changes to rocks exposed on the surface. Rocks and outcrops exposed to the impact of windblown grains on Venus may be veneered with a layer of comminuted debris derived from the grains. Depending upon factors such as orientation with respect to wind direction, local turbulence (as around rocks), and duration of exposure, veneers may range from zero to tens of micrometers in thickness. Remote sensing and instruments that obtain *in situ* measurements of composition for only the surface may not be assessing 'bedrock' materials but, rather, the compositions of windblown particles. Particulate material may be generated on Venus at rates comparable to other terrestrial planets, but its lifetime may be relatively short if it is 'absorbed' as veneers on other rocks. Thus, the rate of erosion for landforms such as craters may be low, as is observed in presently available radar data. Data from MAGELLAN will enable a better evaluation of the states of preservation of impact craters and the degree of their erosion by surficial processes.

What is the Sedimentary 'Budget' on Venus?

Small particles of the size amenable for wind entrainment ($\sim 100\ \mu m$) are produced on planetary surfaces either through primary processes, such as volcanism, or secondary processes, such as release of grains from rocks by chemical weathering (Pettijohn *et al.*, 1972). On Venus, particles should be generated by impact cratering, volcanism, and tectonism – processes that clearly have taken place on the planet's surface. Active volcanism may be occurring on Venus (reviewed by Prinn, 1985; and Wood and Francis, 1988) and could be a source of small particles today. Although impact craters do not appear to be as prevalent as on the Moon or Mars, ejecta from cratering alone on Venus could yield a layer 3 to 70 cm thick of submeter clasts over the entire globe (Garvin, 1989). Chemical weathering of igneous rocks is also expected to release particles (Volkov *et al.*, 1986).

Despite this potential for the production of large quantities of particles on Venus, radar data indicate that substantial parts (perhaps >95%) of the surface is rocky. This suggests several possibilities: (a) particles do not form readily on Venus and the production of particles by volcanism, tectonism, etc., is not as significant as on other terrestrial planets, (b) sedimentary deposits are on a scale not readily observed via currently available radar data (i.e., 30 to 100 km wide Pioneer-Venus Radar Experiment footprint), or (c) particles are recycled and/or removed as part of Venus surface processes. Particles may be accreted to rocks, as discussed in the previous section. Moreover, Venera 15/16 and Earthbased radar images show that many parts of Venus have been fractured by tectonic processes. Fractures range in width from tens of kilometers down to the limit of resolution (~ 1 km) and probably extend to even smaller sizes (meter-widths). These fractured terrains are extensive and could serve as excellent 'traps' for windblown and other sediments, especially if the fractures extend to tens of meters in depth. In some ways, such terrain would be the equivalent to oceans on Earth by removing sediments from the active surface regime. Until the fractures become completely filled, they would remain radar 'bright' or mottled because of their rugged relief. In addition, the rate of tectonic deformation may exceed the rate of infilling by sediments. Mapping of Pioneer-Venus 'radar units' (Davis *et al.*, 1986) shows the presence of 'soils' in fractured terrain, but whether such material is the result of *in situ* weathering or represents transported and trapped material has yet to be determined. MAGELLAN data may allow a determination of whether the 'soils' are *in situ* or deposited.

Magellan data also have the potential for shedding light on the production of particles by providing information on the nature of surface processes. For example, most volcanically-produced particles result from explosive eruptions. Although Head and Wilson (1986) have suggested that explosive volcanism may not occur on Venus under present dense atmospheric conditions, their prediction is model dependent and involves assumptions that are poorly constrained. Moreover, the atmospheric pressure may have been less in the geological past. High resolution Magellan images may enable the question of explosive volcanism to be addressed and, in turn, permit estimates to be made for the amounts of volcanically-produced particles.

Is Wind-Transported Material in Sufficient Quantities to Cause Chemical and Physical Changes on the Surface?

Pioneer-Venus data have shown that topographically high areas on Venus have exposures of material with very high relative permittivities (Pettengill *et al.*, 1988). Although some topographically low areas have also been observed via Earthbased radar to have similar properties (Jurgens *et al.*, 1988), it is interesting to speculate that high areas may have been swept free of fine-grained material, leaving more rugged terrain exposed. Moreover, high-density, high conductivity materials, such as pyrite (Pettengill *et al.*, 1988) or ilmenite (Head *et al.*, 1985) may have remained as a type of windblown 'lag' deposit in the highlands (Greeley *et al.*, 1987). Given the potential flux of windblown particles discussed in the last section, even under gentle winds on the surface, sand would be moved rapidly downwind unless trapped or removed from the active aeolian regime. Simple models of atmospheric circulation for Venus (Dobrovolskis and Saunders, 1986), suggest that winds should transport material generally downslope. On the other hand, Sharpton and Head (1986) have suggested that the highlands have not been significantly altered by erosion or deposition.

Magellan images may enable potential sources for particles to be identified, transportation pathways to be traced, and potential sites of deposition to be recognized via radar backscatter characteristics, emissivity values, and pattern recognition. Radar reflection coefficients vary widely on Venus, from areas considered to be bedrock surfaces to those that are possibly mantled with fine-grained materials. How does the distribution of these areas compare with topography and patterns of atmospheric circulation? Although the circulation model of Dobrovolskis and Saunders (1986) is very 'coarse', it should be adequate to address this first-order question when combined with the MAGELLAN data.

Does Wind-Transported Material Give Rise to Familiar Aeolian Features such as Dunes?

Pathways of windblown sediments might be identified by surface features such as dunes. 'Microdunes' a few cm in size have been produced in Venus simulations. Although it is impractical to simulate larger features, there is nothing inherent in the physics of dune growth to prohibit large dunes on Venus, providing there are sufficient particles and winds to move them. Would such features be recognized on radar images? Blom (1988) and Blom and Elachi (1981, 1987) have shown that dunes as topographic features can be recognized depending upon factors such as dune geometry, radar wavelength, and radar incidence angle in relation to dune orientation. Isolated dunes may also be identified by their shape if they occur on a surface that has a radar backscatter contrasting with that of the dune material. For example, barchan dunes can be distinguished as dark, U-shaped features on a more radar-reflective surface on SIR-A images in the Altiplano of Bolivia (Greeley *et al.*, 1989).

Studies of aeolian processes on Mars have been advanced using so-called 'wind streaks' to identify regions of particle transport, wind directions, and seasonal variability. The martian features are albedo patterns that reflect deposits and zones of erosion that are typically related to topographic features. Could such features exist on Venus and be detected via radar? Perhaps; if windblown materials and processes are occurring, then local-scale (i.e., tens of kilometers) deposits and eroded zones could be expected around topographic features in relation to the wind. As with the dunes, there is the potential for contrasting radar backscatter patterns to enable such features to be distinguished. Such patterns have been identified on radar images on Earth showing 'wind streaks' associated with small hills and cinder cones (Greeley *et al.*, 1989), and have been proposed on Venus from Venera 15/16 images (Barsukov *et al.*, 1986). High resolution MAGELLAN images and multiple-incidence angle coverage during a potential extended mission may enable discovery and mapping of such features.

5. Summary

In the present absence of liquid water on Venus, thermochemical reactions between the atmosphere and surface, aeolian (wind) processes, and downslope movement of material under the influence of gravity are probably the principal means for the exogenic modification of the surface. Theory and experiments suggest a rate of resurfacing by exogenic processes in excess of 2 km/Ga; however, assessments of impact crater degradation derived from radar images of the surface yield orders of magnitude lower rates of resurfacing by surficial materials. Moreover, radar data indicate relatively little sedimentary cover for the areas observed.

The MAGELLAN mission has the potential for addressing many of the questions regarding the surficial geology of Venus. The increase in spatial resolution will enable a refinement of models for the production of particles, tracing potential sediment pathways, and detection of possible sites for deposition. Improvements in rates of resurfacing derived from impact crater frequencies, extension of knowledge to most of the surface of Venus, and better definition of landform degradation models from higher resolution radar images will lead to the understanding of surficial geology in the overall context of the geological history of Venus.

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