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WIND TUNNEL SIMULATIONS OF AEOLIAN PROCESSES

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WIND TUNNEL SIMULATIONS OF AEOLIAN PROCESSES

1.0 Objective

The objective of this project was to determine the characteristics of aeolian (wind) activity as a surface-modifying process on Earth, Mars, Venus, and appropriate satellites. This objective was met through a combination of spacecraft data-analysis, wind tunnel simulations, and terrestrial field analog studies as part of a consortium of investigators from several universities and NASA-Ames Research Center.

2.0 Background

Many physical and chemical processes modify planetary surfaces. Aeolian is defined (Gary et al., 1972) as "Pertaining to the wind; esp. said of rocks, soils, and deposits (such as loess, dune sand, and some volcanic tuffs) whose constituents were transported (blown) and laid down by atmospheric currents, or of landforms produced or eroded by the wind, or of sedimentary structures (such as ripple marks) made by the wind, or of geologic processes (such as erosion and deposition) accomplished by the wind." Thus, any planet or satellite having a dynamic atmosphere and a solid surface is subject to aeolian or wind processes. A survey of the Solar System shows that Earth, Mars, Venus, and possibly Titan meet these criteria. These planets afford the opportunity to study a basic geological process--aeolian activity--in a comparative sense with each planet being a vast natural laboratory having strikingly different environments. Because terrestrial processes and features have been studied for many years, Earth is the primary data base. However, because surface processes are much more complicated on Earth (primarily because of the presence of liquid water and vegetation) many aspects of aeolian processes that are difficult to assess on Earth are more easily studied on other planets.

Wind blowing across a planetary surface has the potential for directly eroding and redistributing material to other areas. Winds transport sediments via three modes: suspension (mostly silt and clay particles, i.e., smaller than about 60 μm), saltation (mostly sand size particles, 60 to 2000 μm in diameter), and surface creep (particles larger than about 2000 μm in diameter). Wind threshold curves define the minimum wind speeds required to initiate movement of different particles for given planetary environments. The ability of wind to attain threshold is a function primarily of atmospheric density, viscosity, composition, and temperature. Thus, the very low density atmosphere on Mars (surface pressure is about 1/200 that of Earth) requires wind speeds that are about an order of magnitude stronger than on Earth.

Aeolian processes are capable of redistributing enormous quantities of sediment over planetary surfaces, resulting in the formation of landforms large enough to be seen from orbit and deposition of windblown sediments that can be hundreds of meters thick. Any process capable of effecting these changes is relevant to understanding the geological environment of planets involved. Furthermore, because aeolian processes involve the interaction of the atmosphere and lithosphere, an understanding of aeolian activity sheds light on meteorological problems. Aeolian activity can be considered in terms of large-scale modifications, small-scale modifications, and as an observable active process.

Large-scale modifications involve features that can be observed from distances of orbiting spacecraft. One of the most useful types of features for interpretation of surface processes is the dune, a depositional landform. Both the planimetric shape and cross sectional profile of dunes can reflect the prevailing winds in a given area. Thus, if certain dune shapes and/or slopes can be determined from orbital data, local wind patterns can be determined. Repetitive viewing of the same dunes as a function of season may reveal seasonal wind patterns.

Small scale aeolian features include ventifacts (wind-shaped rocks) and aeolian sedimentary structures--features that can be observed only directly on the ground or inferred from remote sensing data. Ventifacts can provide information about local wind directions and the lengths of time a surface has been exposed. Identification of ventifacts has relevance to other aspects of planetology. For example, rocks at the martian Viking landing sites that show pitted surfaces have been interpreted as vesicular igneous rocks and are part of the basis for identifying the surrounding plains as volcanic; alternatively, the pitted rocks could be the result of aeolian erosion and are not igneous.

Observations of active aeolian features provide direct information on the atmosphere. For example, crater streaks on Mars are albedo surface patterns that show surface wind direction; they occur in great number over much of Mars. Repetitive imaging of these and other variable features has shown that many of them disappear, reappear, or change their size, shape, or position with time. Mapping the orientations of variable features has been used to derive a near-surface atmospheric circulation model.

Impact crater frequency distributions are widely used in planetary geology to obtain relative dates for different surfaces. On planets having active aeolian processes, the erasure of craters by erosion or burial by aeolian sediments can drastically alter the crater record and invalidate crater-derived ages. Thus, knowledge of rates of aeolian erosion and deposition for a wide range of planetary environments is required in order to assess the possible effects on the impact crater record.

3.0 Approach for Investigating Aeolian Processes

Aeolian processes incorporate elements of geology, meteorology, physics and chemistry. A unified study, therefore, was required using a multidisciplinary approach in which aspects of the aeolian process were isolated for detailed study. In the study of planetary aeolian processes there is little opportunity to field-test extraterrestrial predictions. Thus, we used a somewhat different method, as follows:

1. Identification of the general problem and isolation of specific factors for study (e.g., wind threshold speeds for particles of different sizes on Mars).
2. Investigate the problem under laboratory conditions where various parameters can be controlled for the "Earth case" (e.g., wind tunnel tests of threshold wind speeds).
3. Field test the laboratory results under natural conditions to verify that the simulations were done correctly.
4. Correct, modify, and/or calibrate the laboratory simulations to take into account the field results.
5. Carry out laboratory experiments for the extraterrestrial case duplicating or simulating as nearly as possible the planetary environment involved.
6. Extrapolate the results to the planetary case using the laboratory results and theory (for parameters that cannot be duplicated).
7. Field test the extrapolation via spacecraft observations and apply the results toward the solution of problems involving aeolian processes.

A benefit of this approach is not only to provide a logical means for understanding extraterrestrial problems, but also contributes toward solving aeolian problems on Earth.

4.0 Relevance to NASA-Ames

This research effort is part of the NASA-Ames Aeolian Consortium, formed in the early 1970s to address general aeolian processes in the planetary context. Members of the consortium included:

Ronald Greeley	University of Santa Clara	Geologist
James Iversen	Iowa State University	Aerodynamic engineer
Rodman Leach	University of Santa Clara	Engineer
John Marshall	University of Santa Clara	Geologist
James Pollack	NASA-Ames Research Center	Physicist
Haim Tsoar	Ben Gurion University	Geomorphologist
Joseph Veverka	Cornell University	Planetologist
Wes Ward	U.S. Geological Survey	Geologist
Bruce White	University of California/Davis	Mechanical engineer

Periodic workshops were held to discuss results and to outline areas of future research.

5.0 Facilities

The principal facility in this research effort was the Planetary Geology Aeolian Laboratory at Ames Research Center. This laboratory consists of a space environment chamber (a 4000 m^3 chamber capable of being evacuated to 3 mb pressure) plus the control room and offices. The Mars tunnel, Venus tunnel, and a new Venus simulation apparatus are all housed in the chamber. These wind tunnels and associated apparatus were conceived by members of the Consortium, designed by engineers of the Facilities Services organization of NASA-Ames, and fabricated either through the shops at Ames or on contract from Ames to private concerns.

6.0 Results

Following the approach outlined above, the following provides a summary of results; full citation to published papers and reports is given in section 7.0.

6.1 Results applied to Earth and in the general planetary context

A book entitled *Wind as a Geological Process: Earth, Mars, Venus, and Titan* was published as part of the Cambridge University Press, Planetary Science Series (Greeley and Iversen, 1984), which synthesizes and summarizes much of the work carried out under this project. A review paper, based on the same theme, was presented at a NATO meeting and published as a chapter in a book on comparative planetology as part of the NATO Advanced Study Institute Series (Greeley, 1982).

Aeolian Abrasion

Because wind is an important aspect of erosion on Earth and Mars, a complex series of experiments and numerical analyses was carried out to assess rates of aeolian abrasion (Greeley et al., 1982,1984). Estimation of the rate of aeolian abrasion of rocks requires knowledge of (1) particle flux, (2) susceptibilities to abrasion of various rocks, and (3) wind frequencies. Fluxes and susceptibilities for a wide range of conditions were obtained in the laboratory and combined with wind frequency data for Earth and Mars. On Mars, assuming an abundant supply of sand-sized particles, estimated rates range up to 2.1×10^{-2} cm of abrasion per year in the vicinity of Viking Lander 1. This rate is orders of magnitude too great to be in agreement with the inferred age of the surface based on models of impact crater flux. The discrepancy in the estimated rate of abrasion and the presumed old age of the surface cannot be explained easily by changes in climate or exhumation of ancient surfaces. We considered the primary reason to be related to the agents of abrasion; either windblown grains are in very short supply, or the grains are ineffective as agents of abrasion. At least some sand-sized (~100 μm) grains appear to be present, as inferred from both lander and orbiter observations. High rates of abrasion occur for all experimental cases involving sands of quartz, basalt, or ash. However, previous studies have shown that sand is quickly comminuted to silt- and clay-sized grains in the martian aeolian regime. Experiments also show that these fine grains are electrostatically charged and bond together as sand-sized aggregates. Laboratory simulations of wind abrasion involving aggregates show that at impact velocities capable of destroying sand, aggregates form a protective veneer on the target surface and can give rise to extremely low abrasion rates.

Particle Velocities

Because both rates of wind erosion and rates of sediment transport require knowledge of the velocities of particles related to the wind, a series of experiments was carried out for various planetary conditions (Greeley et al., 1983). Velocities of windblown particles were determined as functions of wind speed, height above the ground, and particle diameter for conditions simulating Earth, Mars, and Venus in environmental wind tunnels. Similar data, although of limited range, were obtained from a field experiment for comparison with the wind tunnel results simulating the terrestrial environment. In general, the results showed that particles travel at higher speeds with increased height above the ground, and that smaller particles travel faster than large ones. However, for a given height above the ground, particle speed does not increase with higher freestream wind speeds. It must be remembered that this is with reference to modal values and not to maximum values; a few particles do increase in velocity with freestream wind speeds. Comparisons of results for Earth, Mars, and Venus reveal some remarkable differences. Most particles achieve speeds nearly equal to freestream wind speed on Venus, but seldom achieve half the wind speed on Mars; Earth cases are of intermediate values. This is attributed to the differences in atmospheric density and to the threshold wind speeds among the three planetary environments. Particles are more easily moved in the dense venusian atmosphere than on Mars; consequently, threshold speeds are very low, and for the range of wind speeds in which most movement is presumed to occur (just above threshold speeds), the grains need not be moving very fast to achieve 100% of the wind speed. Conversely, particles on Mars must accelerate very rapidly to achieve the speed of the high winds required for threshold, and despite the fact that saltation path lengths are long on Mars (White, 1979), most grains fall to the surface before achieving even 50-60% of freestream wind speed.

Yardangs

An important erosion landform seen on both Earth and Mars are elongate, sculpted hills termed yardangs. A study was completed (Ward and Greeley, 1984) involving study of "classic" yardangs in California and development of a formational model through wind tunnel simulation and numerical analyses. Results showed that yardangs at Rogers Lake, Mojave Desert, California, have streamlined forms characteristic of objects eroded by moving fluids, a teardrop shape that approaches an ideal 1:4 width-to-length ratio. In wind tunnel simulations, miniature forms of various shapes changed sequentially by (1) erosion of the windward corner, (2) erosion of the windward slope, (3) erosion of the leeward corners and flanks, and (4) erosion of the leeward slope. Prominent mechanisms in yardang evolution apparently are abrasion at the windward end and deflation and reverse air flow near the middle and at the downstream end. Width-to-length ratios of yardangs are grossly similar to those of some fluvial and glacial streamlined landforms. The low kinetic energy of wind relative to ice and water, the erosional resistance to wind of most rocks, the rarity of long-term, unidirectional winds, and the presence of running water, topographic roughness, and vegetation all limit the abundance of yardangs.

6.2 Results applied to Mars

As reviewed by Greeley et al. (1981), Earth-based observations and spacecraft results show that aeolian processes are currently active on Mars. Analyses of various landforms, including dunes, yardangs, and mantling sediments of probable aeolian origin, suggest that aeolian processes have been important in the geological past. Dust storms originate in specific areas of Mars and are most vigorous during the martian summer in the southern hemisphere. In order to understand aeolian processes in the low surface pressure (~7 mb), carbon dioxide atmosphere of Mars, a special wind-tunnel was fabricated to carry out investigations of the physics of windblown particles under martian conditions. Martian threshold wind speeds have been derived for a range of particle diameters and densities; the threshold curve parallels that for Earth but is offset toward higher wind velocities by about an order of magnitude. The "optimum" size particle (the size most easily moved by minimum wind) is about 100 μm in diameter; minimum freestream winds to generate particle motion are about 40 m/s. Grains smaller than 100 μm ("dust") require increasingly higher winds to initiate threshold; yet, estimates of grain sizes in the dust clouds are in the size range of a few microns and smaller. Because the Viking Lander has recorded winds no stronger than those for minimum threshold, it is suggested that some other mechanism than uniform strong winds is required for "dust" threshold. Experiments and theoretical considerations suggest that such mechanisms could be cyclonic ("dust devil") winds, a saltation cascading effect by larger (more easily moved) particles, and injection of fine grains into the wind stream by outgassing volatiles absorbed on the grains.

To refine the general results described above, a series of wind tunnel experiments was run in which the "working" fluid was carbon dioxide to simulate more closely the atmospheric conditions on Mars (Greeley et al., 1980). Wind friction threshold speeds (u_{*t}) for particle movement (saltation) were determined in a wind tunnel operating at martian surface pressure with a 95 percent CO_2 and 5 percent air atmosphere. The relationship between friction speed (u_*) and freestream velocity (u_∞) is extended to the critical case for Mars of momentum thickness Reynolds numbers (Re_θ) between 425 and 2000. It is determined that the dynamic pressure required to initiate saltation is nearly constant for pressures between 1 bar (Earth) and 4 mb (Mars) for atmospheres of both air and CO_2; however, the threshold friction speed (u_{*t}) is about 10 times higher at low pressures than on Earth. For example, the u_{*t} (Earth) for particles 210 μm in diameter is 0.22 m/s and the u_{*t} (Mars, 5 mb, 200 K) is 2.2 m/s.

Wind streaks constitute the most abundant aeolian feature on Mars and numerous explanations have been offered to explain their origin(s). As a means of relating the size, shape, and geometry to rates of particle erosion/deposits, a model was developed and refined (Iversen and Greeley, 1984), based on wind tunnel simulations. This model enables the estimation of the total volume of material eroded to produce dark streaks, utilizing sequential orbital images.

6.3 <u>Results applied to Venus</u>

Small particles and winds of sufficient strength to move them have been detected from Venera and Pioneer-Venus data and suggest the existence of aeolian processes on Venus. The Venus Wind Tunnel (VWT) was fabricated in order to investigate the behavior of windblown particles in a simulated venusian environment (Greeley et al., 1984). Preliminary results show that sand-size material is readily entrained at the wind speeds detected on Venus and that saltating grains achieve velocities closely matching those of the wind. Measurements of saltation threshold and particle flux for various particle sizes have been compared with theoretical models which were developed by extrapolation of findings from martian and terrestrial simulations. Results are in general agreement with theory, although certain discrepancies are apparent which may be attributed to experimental and/or theoretical modeling procedures. These findings enable a better understanding of venusian surface processes and suggest that aeolian processes are important in the geological evolution of Venus.

To assess the types of small-scale aeolian features on Venus, a series of tests were run to develop bedforms in the Venus Wind Tunnel (VWT) simulating the average venusian environment (Greeley et al., 1984). Even at the low wind speeds measured on Venus, dunelike structures form in fine-grained quartz sands (particles 50-200 μm in diameter). The dunelike structures, referred to as microdunes, are considered to be true dunes analogous to those on Earth because they have (1) slip faces, (2) a lack of particle-size sorting, (3) a low ratio of saltation path length to dune length, and (4) internal cross-bedding. The microdunes typically produced in the VWT are 9 cm long and 0.75 cm high. It is proposed that there may be fields of microdunes on Venus that are capable of very fast rates of migration and that they may grow into features much larger than those observed in the VWT. However, neither dunes nor other types of features develop above a wind speed of ~1.5 m/sec; at this wind speed, the bed is flat and featureless. Thus, it is predicted that relatively short periods of higher winds may destroy microdunes and other small bedforms which could account for the sparsity of definitive aeolian features observed in Venera images. Some apparent cross-bedding observed in Venera images, however, could represent preserved aeolian structures.

The wind tunnel results simulating Venus reveal a hitherto unknown mode of transport by the wind (Greeley and Marshall, in press). Simulations of venusian wind processes show that particles are moved by rolling at wind speeds as much as 30% lower than those required for saltation threshold. This mode of wind transport is only observed for sustained periods in water on Earth; thus, there are similarities between aqueous fluid transport on Earth and atmospheric transport on Venus. The formation of small sand ridges and grooves oriented parallel to the wind direction are associated with the rolling of grains in venusian simulations and may be unique aeolian features on Venus. The rolling mode of wind transport on Venus may be important from several considerations:

a) Frequency of transport: Because threshold wind speeds for rolling are significantly lower than for continuous saltation, the occurrence of aeolian processes may be more frequent than if based solely on saltation threshold, despite the relatively gentle winds recorded on Venus.

b) Interpretation of venusian surface: If some bedforms are the consequence of a mode of fluid transport that is unique to the venusian environment, then interpretations of the surface should not rely solely on terrestrial aeolian (or water) analogs.

c) Movement of large particles: Particles 4-5 mm may be easily moved by rolling (Fig. 1) by winds within the range expected on Venus.

d) Flux of windblown material: Previous estimates of the amount of material moved by the wind on Venus (15) do not take into account the rolling mode, but are based solely on saltation. Thus, substantial material may be moved by surface creep involving rolling (especially for large grains) under relatively low (sub-saltation) wind speeds. However, the total flux may still be far less than that of sediments transported by water on Earth (16).

e) Small-scale surface features: Small features transverse to the wind such as ripples and microdunes did not develop in experiments in which transport was solely by rolling. However, grooves and ridges parallel to the wind formed and might be expected on Venus. The length of these features was governed by the size of the wind tunnel and it is possible that on Venus they could extend for tens or even hundreds of meters. Depending upon the characteristics of radar imaging systems, such as wavelength, and the geometry of the radar beam, radar signatures from the surface of Venus could be influenced by the presence of these grooves and ridges. In these preliminary results, we note that while there is an association of rolling with longitudinal bedforms, these features are not necessarily a function of this mode of transport.

In conclusion, wind tunnel experiments simulating venusian surface conditions demonstrate that rolling of particles may be an important mode of transport by winds on Venus and that aeolian processes in the dense atmosphere may share attributes of both aeolian and aqueous environments on Earth.

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