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Wind as a geological process

1.1 Introduction

Beginning with the first tentative probes into space in the mid-1960s, the geological exploration of the solar system has revealed a remarkable diversity in the planets and their satellites. Each planetary body displays combinations of surface features that reflect unique geological histories and environments. Yet, when the surfaces of the terrestrial planets and satellites are analyzed in detail, we find that many of them have experienced similar geological processes in their evolution.

The discipline of *comparative planetary geology* has as its goal the definition of the fundamental processes that have shaped and modified the planets, satellites and other 'solid surface' bodies in the solar system. For simplification, we shall refer to all such objects simply as *planets*. The giant gaseous planets, such as Jupiter and Saturn, are excluded from study because they apparently lack solid surfaces and thus are not appropriate for geological analyses. The goal of planetary geology is achieved by determining the present state of planets, by deriving information of their past state(s) – or geological histories – and by comparing the planets to one another.

Comparative planetary geology has shown that nearly all of the planets have been subjected to major geological processes, including impact cratering, volcanism, tectonism (crustal deformation), and gradation. Gradation involves the weathering, erosion, and deposition of crustal materials through the actions of various agents, such as wind and water. This book deals with wind, or *aeolian*, processes (Fig. 1.1). Aeolian is defined (Gary *et al.*, 1972) as 'pertaining to the wind; especially 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 (Table 1.1). 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 which has strikingly different environments. Because terrestrial processes and features have been studied for many years, Earth is the primary data base for interpreting aeolian processes on the planets. However, because surface processes are much more complicated on Earth – primarily because of the presence of liquid water and vegetation – some aspects of aeolian processes that are difficult to assess on Earth are easier to understand on the other planets. For example, on Mars the lack of competition from other processes during the

Fig. 1.1. View of the great dust storm of December, 1977, in the Central Valley of California, showing dust originating near the base of the mountains to the left and rising to several hundred meters. Dust storms have direct cultural and geological effects and are part of the general aeolian regime. (Copyright 1978, UNIFO Enterprises, San Francisco, California.)

Table 1.1. *Relevant properties of planetary objects potentially subject to aeolian processes*

	Venus	Earth	Mars	Titan
Mass (Earth = 1)	0.815	1	0.108	0.02
Mass (kg)	48.7×10^{23}	59.8×10^{23}	6.43×10^{23}	1.34×10^{23}
Density (water = 1)	5.26	5.52	3.96	1.90
Surface gravitational acceleration (m/sec^2)	8.88	9.81	3.73	1.36
Diameter (km)	12 104	12 756	6787	5140
Surface area (km^2)	4.6×10^8	5.1×10^8	1.4×10^8	8.3×10^7
Atmosphere (main components)	CO_2	N_2, O_2	CO_2	N_2
Atmospheric pressure at surface (mb)	9×10^4	10^3	7.5	$\approx 1.6 \times 10^3$
Mean temperature at surface (°C)	480	22	−23	−200
Liquid water on surface	no	yes	no	no
Orbital radius (AU)	0.72	1.00	1.52	9.53
Orbital period (yr)	0.62	1.00	1.88	29.6[a]
Orbital eccentricity	0.007	0.017	0.093	0.056[a]
Obliquity (°)	< 3	23.5	25.1	—
Axial rotation rate (days)	243 (retrograde)	1	1.027	—
Solar flux (erg/(cm^2 sec))	2.61×10^6	1.37×10^6	0.59×10^6	0.15×10^5

[a] Values for the planet Saturn.

last aeon or more permits the cumulative effect of aeolian processes to be relatively better observed than on Earth.

In this chapter we discuss the general approach for investigating aeolian processes in the planetary context and consider the relevance of aeolian processes to other geological problems. Finally, we provide an overview of aeolian activity on Earth, Mars, Venus, and Titan.

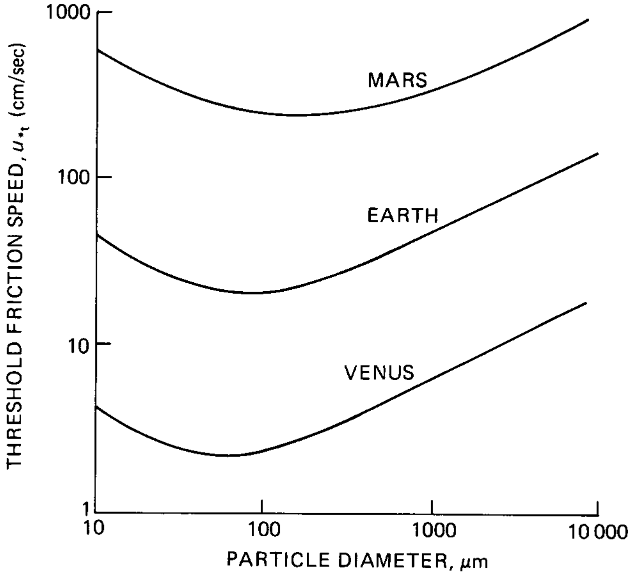
1.2 Approach to the problem

Aeolian processes incorporate elements of geology, meteorology, physics, and, to some degree, chemistry. A unified study of these processes therefore requires a multidisciplinary approach. The approach commonly employed is not only multidisciplinary but combines field studies with laboratory simulations and theory.

Let us take the determination of the *threshold curve* as an example of this multidisciplinary, combined approach. The threshold curve (Fig. 1.2; Appendix A) relates the minimum wind speeds required to set particles of different sizes into motion and is probably the most important relationship within the various aspects of aeolian processes. The threshold curve for Earth was first derived by R. A. Bagnold (1941), a British Army engineer who spent considerable time in the deserts of Egypt. Bagnold conducted a series of wind tunnel experiments in which he varied particle size to determine the minimum wind speeds necessary to set the particles into motion. Wind velocities were expressed in terms of the shear stress exerted on the sand surface by the wind, which is a function of the wind velocity profile. He then field tested the results under natural conditions, making careful measurements of wind velocity profiles and various particle characteristics.

Using the results from his laboratory experiments and field studies, Bagnold then derived the mathematical expressions for the movement of sand by the wind, in terms of the fundamental physics that are involved. Thus, he was concerned with a *geological* problem (windblown sand) that required knowledge of *meteorology* (wind velocities above the sand

Fig. 1.2. Comparison of the threshold friction speed versus particle diameter for Mars, Earth, and Venus. (From Iversen *et al.*, 1976*b*.)



surface), and *physics* (expression of the movement of the sand). His approach was to combine engineering practices utilizing wind tunnels with geological and meteorological field methods to derive mathematical models of the general problem.

This same approach is used to study aeolian processes on the planets. In the mid-1950s, planetologists first began to consider the possibility that Mars may experience aeolian processes. Dean McLaughlin (1901–65), a professor at the University of Michigan, used his combined training and interests in astronomy and geology to analyze the distribution of albedo markings on Mars. From his analyses, he concluded (McLaughlin, 1954*a*,*b*; reviewed by Veverka & Sagan, 1974) that many of the markings were aeolian and derived a map of deduced wind directions, which is remarkably similar to wind patterns based on recent spacecraft data. Later, Sagan & Pollack (1969) adopted the basic expressions for wind threshold speeds derived by Bagnold, substituted the appropriate values for the martian environment (gravity and atmospheric density), and derived a threshold curve for sand movement on Mars. Although there were a great many uncertainties in their extrapolation, because knowledge of the martian environment was extremely limited, it was the first attempt to apply terrestrial aeolian parameters to an extraterrestrial problem.

Knowledge of the martian environment expanded with each of the United States' missions to Mars – Mariner 4 (1965), Mariners 6 and 7 (1969), Mariner 9 (1971–72), and the Viking mission (1976–79) – as well as the Soviet Orbiters, Mars 3 (1971) and Mars 5 (1974). Concurrent with incoming spacecraft data, an understanding of the dynamics of carbon dioxide at low atmospheric densities and knowledge of particle motion in the martian environment were gained through various laboratory simulations (Hertzler *et al.*, 1967; Iversen *et al.*, 1973; Greeley *et al.*, 1976, 1980*a*). These simulations culminated in a series of wind tunnel experiments in which atmospheric composition and density were duplicated for Mars. But because some martian parameters, such as the lower gravity, could not be simulated in the experiments, certain parameters had to be analyzed theoretically in order to derive the final threshold curve for Mars, shown in Fig. 1.2.

The ultimate test for this approach to planetary problems is a measurement made on the planet concerned. In the case described for Mars, measurements of winds obtained through the meteorology experiment on board the Viking Landers, and observations of dust storm activity, show that the threshold curves are essentially correct (Sagan *et al.*, 1977).

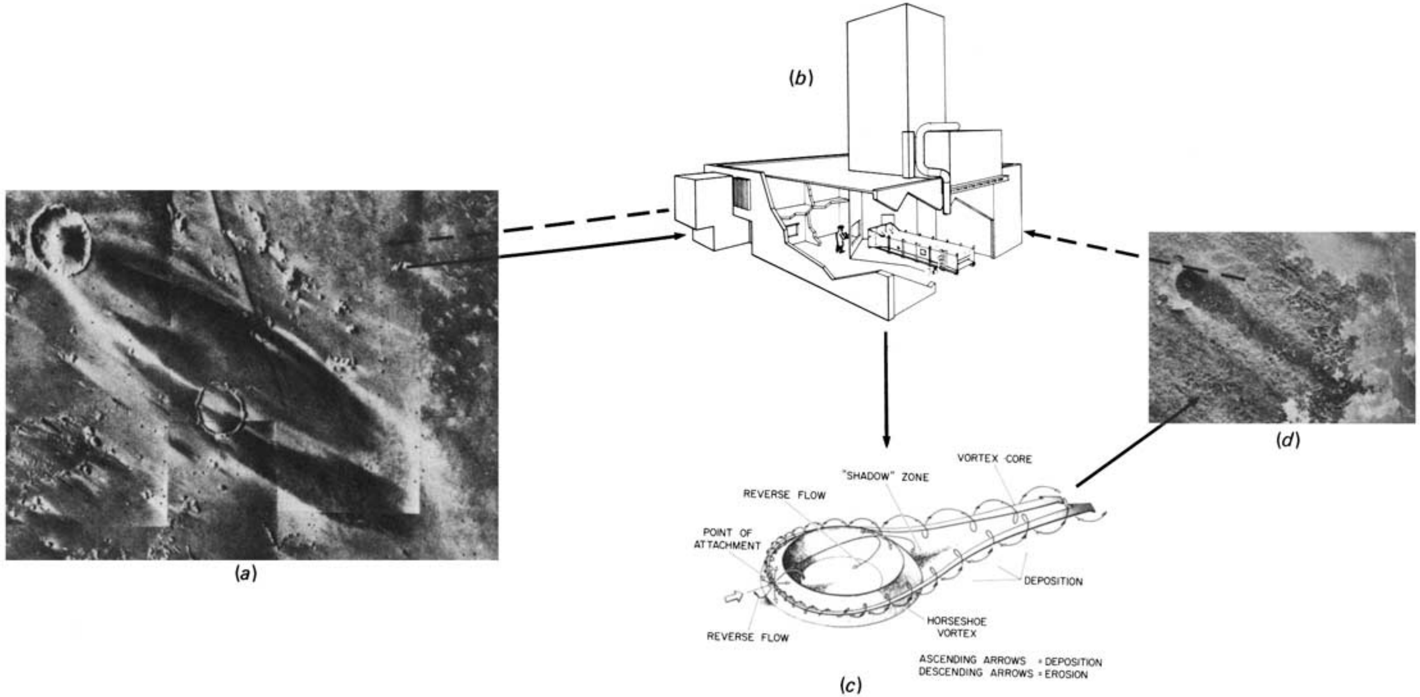


Fig. 1.3. Illustration of the three-fold approach to problems in planetary geology, combining spacecraft data analysis with laboratory simulations and field studies: (*a*) *definition of the planetary problem* (formation of dark streaks associated with wind swept craters on Mars), (*b*) *laboratory simulation* 'Earth-case' (winds blown across the model of a crater), (*c*) *derivation of the model* (air flow patterns and zones of wind erosion and deposition are determined from the wind tunnel tests), (*d*) *field study* (measurements of the air flow and geological studies of the natural site at Amboy lava field, California). The results from the field study are used to verify–calibrate–modify the wind tunnel simulations; then, once confidence in the methodology is obtained for the 'Earth-case', the wind tunnel tests are run under conditions simulating the martian environment as closely as possible. Extrapolation to the planetary case usually requires the use of theory with the simulations because some parameters, such as gravity, cannot be duplicated in experiments conducted on Earth. In the example shown here, dark crater streaks on Mars were found to be erosional features resulting from the vortices shed from the rims of the craters. (After Greeley *et al.*, 1974*b*.)

We can outline a general procedure for studying aeolian processes in the planetary context, using the example shown in Fig. 1.3 (Greeley, 1982):

(1) identification of the general problem and isolation of specific factors for study;
(2) investigation of the problem under laboratory conditions simulating the 'Earth case' where various parameters can be controlled;
(3) field testing of the laboratory results under natural conditions to verify that the simulations were done correctly;
(4) correction, modification, and/or calibration of the laboratory simulations to take the field results into account;
(5) laboratory experiments for the extraterrestrial case to duplicate or simulate, as nearly as possible, the planetary environment involved;
(6) extrapolation to the planetary case using a combination of the laboratory results and theory for parameters, which cannot be duplicated, such as gravity differences;
(7) field testing of the extrapolation via spacecraft observations and application of the results to the solution of the identified problem.

Although we are a long way from carrying out this approach in the study of all aspects of aeolian processes for Earth, Mars, Venus, and Titan, the results presented here draw upon this general approach as much as possible. As one might expect in defining the various problems, we commonly find that many aspects of aeolian processes are not well understood, even for Earth, let alone for other planetary environments. Consequently, a benefit of the approach outlined here is not only to provide a logical means for solving extraterrestrial problems, but to contribute toward solving problems dealing with aeolian processes on Earth as well.

1.3 Significance of aeolian processes

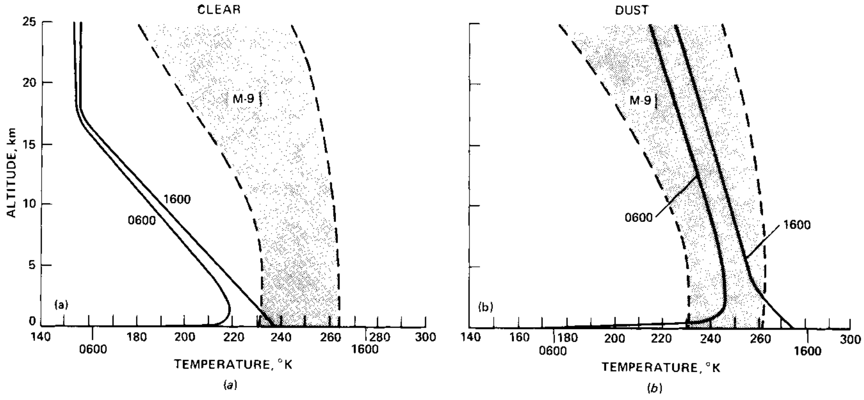
It is estimated that more than 500×10^6 metric tons of dust (particles $\leqslant 20\ \mu$m) are transported annually by the wind on Earth (Peterson & Junge, 1971). Dust storms reduce visibility on highways and are responsible for loss of life and property due to many accidents each year. Atmospheric dust, whether raised by winds or injected into the atmosphere by volcanic processes, can also have a significant effect on temperature. Such effects have been documented on Earth, both locally and globally, and have been observed on Mars, as shown in Fig. 1.4. Thus, aeolian processes can have a direct effect on changing the climates of the planets.

Windblown sand (particles 0.0625–2 mm) causes numerous problems, primarily through abrasion of man-made objects and encroachment on cultivated lands and developed areas. For example, special precautions must be taken to prevent erosion of structures by windblown sand in some regions. As shown in Fig. 1.5, the lower parts of power poles in sandy regions must be sheathed in metal to prevent their being worn away by sands driven by the wind.

Any process that is capable of eroding and transporting vast quantities of material is important in the geological context. Much of the present landscape in desert regions results from aeolian processes. Vast areas are blanketed with sheets of windblown silt and clay, called *loess* (Fig. 1.6). It is estimated that one-tenth of Earth's land surface is covered with loess and loess-like deposits in thicknesses of 1–100 m (Pécsi, 1968). Loess soils constitute some of Earth's richest farmlands.

The geological column shows ample evidence of aeolian processes throughout Earth's history, as reviewed by Reineck & Singh (1980). Glennie (1970) discusses ancient aeolian sediments and provides a list of factors to enable the recognition of windblown deposits. Thick sand

Fig. 1.4. Effect of atmospheric dust on atmospheric temperatures on Mars (modeled). (*a*) Two modeled temperature profiles (morning, 0600, and afternoon, 1600) as a function of the height above the surface for clear atmospheric conditions. (*b*) Modeled temperature profiles during the global dust storm. Model values are similar to measurements made by Mariner 9 during the dust storm of 1971–72 (shaded area). (Pollack, 1979, after Gierasch & Goody, 1973.)



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deposits (Fig. 1.7) occur in many areas and represent ancient sand 'seas'. For example, the Permian Age Coconino Sandstone is tens to hundreds of meters in thickness and covers thousands of square kilometers of the Colorado Plateau. Enormous cross-beds and other sedimentary structures attest to its aeolian origin. In some cases, windblown sediments are important reservoirs of water and petroleum. Understanding sedimentary structures within these aeolian deposits and knowledge of their environments of deposition can help in fully realizing their potential as supplies of water and oil.

1.3.1 *Relevance to Earth*

The understanding of aeolian processes is essential to the control of such processes at those places on Earth where control is important. The necessity for control can be generally classed into three groups – environmental, agricultural, and transportation – although there are significant problems in other endeavors as well. Environmental problems have to do with the effects of dust on health, visibility, and climate, as well as on engineering considerations such as abrasion by windblown grains. Agricultural problems involve soil erosion by wind and the effects on plants of blowing soil and sand. The effects on transportation include the protection from, or removal of, blown snow or sand on highways, railroads, and airport runways.

Desertification is a term coined for the conversion of land to deserts. Although the causes of desertification are controversial, thousands of square kilometers are converted to deserts annually. Whether primarily man-caused or resulting from natural cycles on Earth, aeolian processes play a significant role in desertification. For example, during periods of drought, topsoil dries out and is easily removed by the wind, converting arable land to desert. By understanding the relationships between surface roughness (e.g., windbreaks) and threshold wind speeds, it is possible to retard topsoil erosion and to slow down, or halt, desertification in some areas.

The desertification problem is enormous. Although more than one-third of Earth's land is arid or semiarid, somewhat less than one-half of this area is so dry that it cannot support human life. Over 600 million people live in dry areas, and about 80 million of these live on lands that are nearly useless because of soil erosion and encroachment of sand dunes or other effects of desertification (Eckholm & Brown, 1977). Desertification of arid lands, much of which is the result of human activity, is evident on all inhabited continents of Earth, but the largest areas of severe desertification are in

Fig. 1.5 (a)

(b)