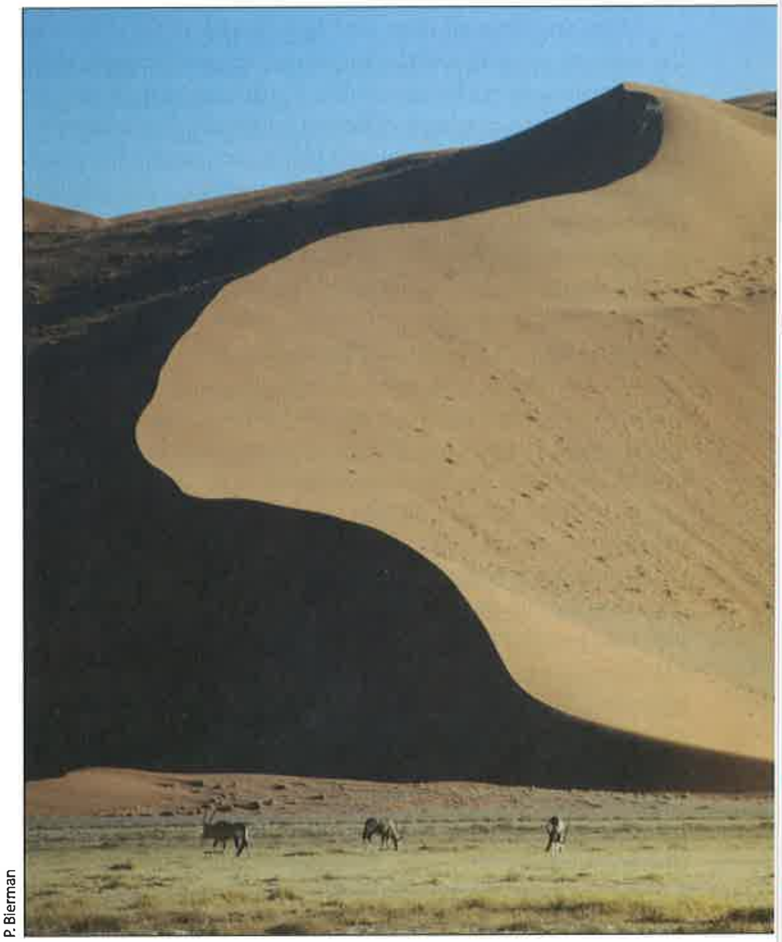
Wind as a Geomorphic Agent 10

Introduction

Wind, the coherent movement of the fluid we call air, affects surface processes everywhere on our planet. **Aeolian,** or wind-driven, sediment transport connects different sedimentary environments, some of which are adjacent, others of which are separated by long distances. Along coasts, wind moves sand into and out of storage in coastal dunes and is effectively a local extension of the longshore drift system. On mid-ocean islands, such as Hawaii, wind delivers quartz-bearing dust from Asia thousands of kilometers away. Sediment mantling the abyssal plains of the deep ocean is largely wind-derived, and aeolian dust plays a key role in delivering iron, an important marine fertilizer, to the oceans. Soils developed on wind-transported fine-grained sediment are very fertile (for example, the Palouse of eastern Washington State, famous for wheat farming) and important agriculturally around the world. Desert pavements characteristic of arid regions owe their existence largely to wind.

The geomorphic influence of wind on landscapes is not uniform across the surface of Earth. Wind-driven surface processes are most easily detected where wind-transportable sediment is abundant and where Earth's other geomorphically active fluid, water, and therefore vegetation, is relatively scarce. Such locations include both arid deserts and other areas with significant water deficits, such as coastal zones with highly permeable soils, sandy glacial margins, and exposed sandbars in broad river corridors. In areas where water is abundant, fluvial and hillslope processes are typically quite active, vegetation is dense,


P. Bierman

Arm of a star dune in the Namibian Sand Sea (erg) near Sossusvlei with oryx, a type of antelope, grazing in the foreground. The star dunes here can be up to several hundred meters high.

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and the role of aeolian activity is harder to decipher. But aeolian geomorphic features are by no means restricted to deserts; the influence of wind and wind-transported sediment is felt across all of Earth's surface. Wind dominates contemporary surface processes on Mars and perhaps on other terrestrial planets with atmospheres.

Most aeolian sediment is rich in quartz (SiO_2) because the mineral is hard, weathering-resistant, and a major constituent of many rocks exposed at Earth's surface. However, there are dunes made of different minerals. For example, the dunes at White Sands, New Mexico, are made of gypsum (calcium sulfate) derived from a nearby playa, a dry lakebed **[Photograph 10.1]**.

The stratigraphic record of wind-deposited sediment can be deciphered to understand the history of our planet. For example, **aeolianite,** indurated coastal dune material cemented by $CaCO_3$ derived from the dissolution of shell fragments within the sand **[Photograph 10.2]**, overlies many elevated marine terraces. Aeolianite-capped terraces, dated using a variety of luminescence techniques, provide critical evidence for sea-level heights in the past, allowing us to understand the timing and magnitude of sea-level change over the past half million years.

Biologic activity greatly reduces the relative geomorphic effectiveness of aeolian processes. The roots and decomposition products of vegetation bind soil particles together, providing apparent cohesion. Plants also change airflow patterns and speed, reducing wind's importance as a sediment entrainment and transport mechanism, as well as catalyzing aeolian sediment deposition as rough surfaces slow air movement. Wind is an effective geomorphic agent in deserts primarily because arid regions lack widespread and continuous vegetation cover. Biologic crusts, such as those common on dry-land surfaces, limit wind erosion in deserts. They do this by making the soil surface cohesive and thus allowing otherwise erodible soils to remain stable even under high winds **[Photograph 10.3]**. Such cohesion allows granular soil material (such as sand and silt) to resist entrainment by wind.

M. Wilson

PHOTOGRAPH 10.2 Aeolianite. Several-meter-high Holocene aeolianite (calcium-carbonate-cemented dune sand) outcrop in the Bahamas.

The geomorphic effects of wind can be significant. Strong persistent wind may remove the vegetation-anchoring earth materials including soil, weathered rock, and dune sands. Moving air can be a major agent of vegetation disturbance and thus a catalyst for surface change. Wind-driven waves batter beaches and cliffs and break up arctic sea ice important to the climate system. Prevailing winds carry moisture upslope where orographic precipitation, induced as air masses are forced to rise over mountains, initiates fluvial and hillslope processes. In dune fields, wind transports sand many kilometers. Fine-grained particles, such as silt and volcanic ash, are carried around the globe, suspended by wind and deposited far from their sources. Wind-transported dust is a critical component of many soils including those that underlie the breadbaskets of the world.

Dennis Flaherty/Science Source

PHOTOGRAPH 10.1 Sand Dune. Ripple-covered gypsum sand dune at White Sands, New Mexico. Shrubs and small trees provide scale.

National Park Service

PHOTOGRAPH 10.3 Biological Soil Crust. Biological soil crust in Canyonlands National Park in southwest Utah holds sediment in place over rock and resists erosion by wind and water.

Air as a Fluid

Air is a fluid moving across Earth's surface. Air behaves similarly to water, except that air is less viscous, and because wind is a reflection of the atmospheric pressure gradient, air flows both up and down topographic gradients. Both flowing air and water are steered by and interact with the land surface; however, the distribution of flowing air and water are different. Because the atmosphere surrounds the planet, all parts of Earth's surface can be affected by wind. In contrast, much of the liquid water on Earth is either in the oceans, where motion and thus kinetic energy are concentrated in currents and waves that do most of their geomorphic work on shorelines, or in stream channels, where kinetic energy is dissipated by flow around roughness elements such as trees, boulders, or rough banks and used to entrain sediment along channel margins.

The material properties of water and air are strikingly different. Air is much less dense than water. At 20°C, water is more than 800 times denser than air and the dynamic **viscosity** of water (its resistance to deformation) is more than 50 times greater than that of air. These differences mean that transfer of momentum will be more efficient between water and sediment than between air and sediment. Solid material, such as silt and sand, will settle much more rapidly through less dense and less viscous air than through denser and more viscous water **[Figure 10.1]**. In practice, the low viscosity and density of air means that wind can only transport smaller sediment grain sizes such as clay, silt, and sand. For the most part, transport of gravel and boulders must be left to hillslope and fluvial processes. Only in exceptionally windy places (such as the Dry Valleys of Antarctica), where there is scant if any surface vegetation to provide roughness and anchor sediment, is gravel moved by wind.

The movement of air, just as that of water, can be laminar or turbulent. Turbulent flow is chaotic and difficult to predict; the velocity (speed and direction) of turbulent airflow varies rapidly and turbulent flows are effective at mixing the atmosphere. For example, on a calm morning, smoke from a chimney may rise slowly and steadily into the sky. Flow in a stable atmosphere is mostly laminar; there is little turbulence. The physics of laminar flow is determined primarily by the viscosity of air. As the day goes on and Earth's surface is heated by the Sun, packets of warm, less-dense air rise into the atmosphere, and airflow becomes more chaotic or turbulent; the same column of smoke is rapidly mixed and cannot be tracked far from the chimney. Turbulence, and the eddies and wind gusts it spawns, are geomorphically important because bursts of higher-than-average wind speed can initiate and maintain sediment movement.

Unlike fluvial sediment, the deposition of which is constrained by the location of channels and the elevation and location of base level, aeolian sediment, once entrained and in motion, can be transported just about anywhere the wind blows. Windblown sand can move up topographic gradients and around obstacles such as outcrops or hills.

Both water and air are fluids, but water is a much more viscous fluid than air. As a result, particles settle more slowly through water than they do through air. For example, the settling velocity of a 1 mm particle in water is 100 times slower than the same particle settling through air.

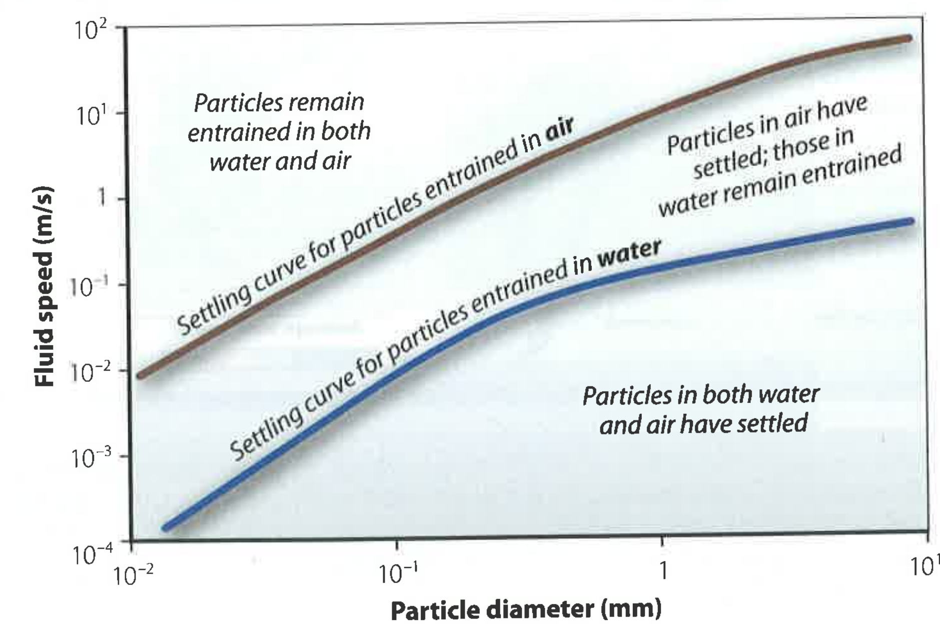


FIGURE 10.1 Comparison of Water and Air as Fluids. The difference in viscosity and density causes particles to settle more rapidly in air than in water.

Globally, aeolian transport moves about 10 percent of the mass of sediment moved by rivers.

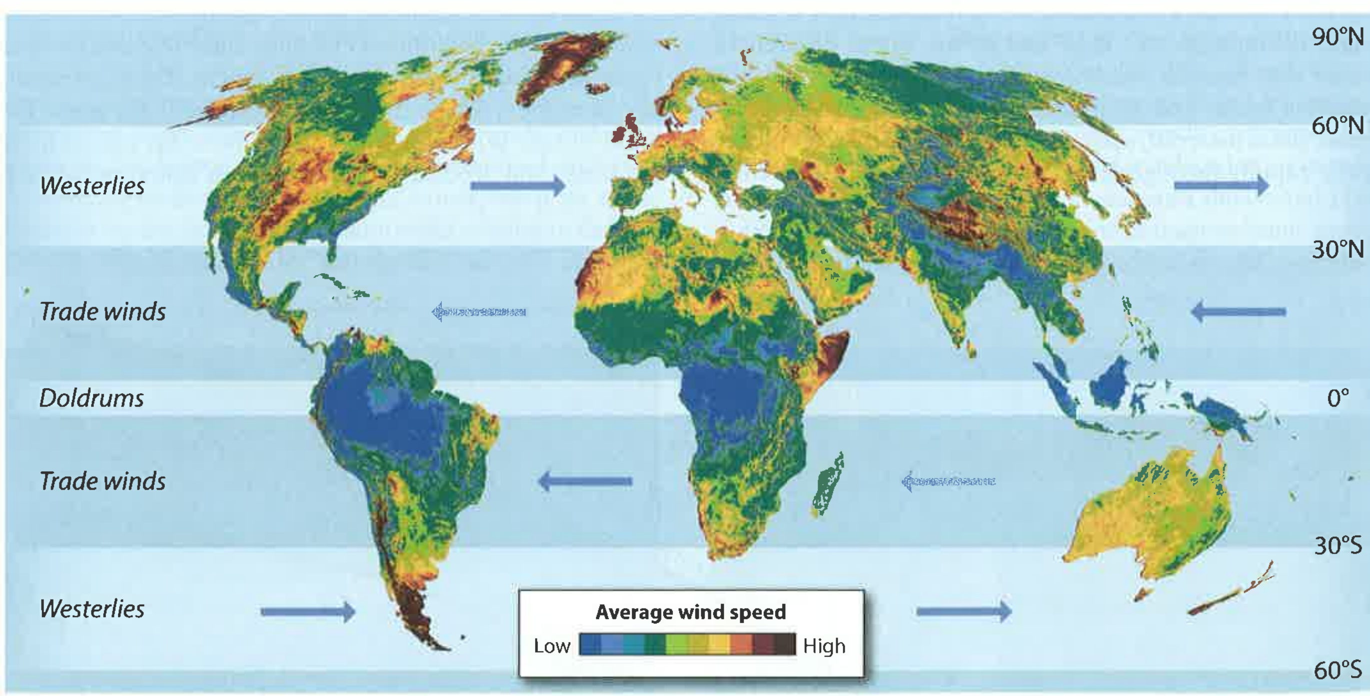
Wind Patterns and Speeds

Wind speed matters geomorphically because it, along with vegetation, controls whether a particle of a given size is stable or if it will be moved by rolling, saltation, or suspension. At the global scale, wind speeds are high where the pressure gradient is steep, such as between the adjacent high-pressure and low-pressure systems that drive the trade winds. On a regional scale, wind speeds are often high on mountain ridges, where air is forced up and over topography, and at mountain passes, where air is funneled by topography into a restricted area. At the human scale, wind speeds are lower near the ground as air moves around obstacles such as trees, bushes, and rocks. Such **terrain roughness** creates turbulence and thereby serves to dissipate some of the kinetic energy of the air, lowering the wind speed.

Large atmospheric circulation cells set global patterns of wind speed and direction as well as moisture distribution and thus provide a first-order control over the geomorphic effectiveness of wind. There are substantial differences in average wind speeds and direction around the world **[Figure 10.2]**. Near the equator, wind speeds tend to be low. These are the **doldrums**, the equatorial intersection of the northern and southern Hadley cells where net air motion is upward (see Figure 1.5). The geomorphic effect of wind in many equatorial regions is limited (other than in coastal areas) because near the equator moisture is commonly sufficient to support dense vegetation, preventing wind erosion and transport of sediment.

Farther north, in the belt of **trade winds**, average wind speeds are higher. In general, between the belts of trade winds and westerly winds (25 to 35 degrees north and south latitude) are dry areas where aeolian activity is more important than elsewhere on Earth. These low latitudes are dry because air masses are generally descending there, the result of convergence between the downflowing limbs of the Ferrel and Hadley atmospheric circulation cells (see Figure 1.5). As the air descends, it warms from the increase in pressure and dries as the **relative humidity** (the percent saturation of the air mass with water vapor) decreases. In general, continental areas where air motion is downward include some of the world's great deserts such as the Sahara (15 to 30 degrees north latitude), and Namib, Kalahari, and Australian deserts (which all lie between 20 and 30 degrees south latitude).

In the Southern Hemisphere, the highest wind speeds are found in the stormy latitudes between the tip of South America and Antarctica. Named by sailors the roaring 40s, furious 50s, and screaming 60s, wind speeds across the Southern Ocean are on average quite high because there is no land to block the wind and dissipate some of the wind energy through roughness-induced turbulence.



Wind speeds are not uniform on Earth's surface. Winds speeds are low in the **doldrums** near the equator and high in the storm tracks, known as the roaring 40s, at 40° to 50° north and south latitude. Winds are high in mountainous areas such as the Himalaya and the Rocky Mountains. Wind direction at a global scale is controlled by variations in the distribution of incoming solar radiation and the effects of Earth's rotation. These large-scale effects lead to predominant wind directions that vary with latitude.

FIGURE 10.2 Average Wind Speeds on Earth. Average wind speeds are controlled in large part by the position of global circulation cells and major topographic features.

Vertical Distribution of Wind Speed

Wind speed decreases near the boundary between Earth's surface and the atmosphere due to the drag caused by surface roughness. This means that large boulders, tall trees, and high standing outcrops are more likely to experience high winds than material sitting directly on the ground. However, the concentration of wind-suspended sediment is higher closer to the ground; thus, abrasion, one of the geomorphic effects of wind, is more likely to occur at elevations below where the highest wind speeds are found.

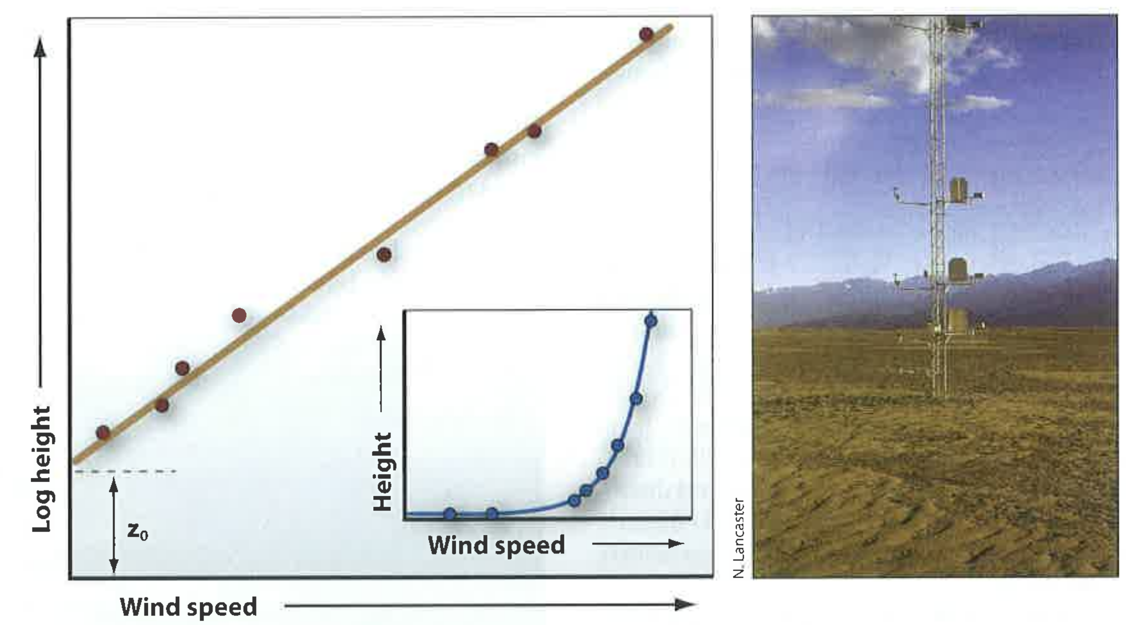
The speed of air above the ground surface is usually described by the Karman/Prandtl model, which is based on observations of increasing wind speed with the logarithm of height above the ground **[Figure 10.3]**. At some small height above the ground, mean wind speed goes to zero, the z intercept of the curve, which is known as the **roughness length** (z_0). Physically, z_0 is related to the roughness of the bed and implies there is a boundary layer in which the net wind speed is zero. The Karman/Prandtl model is a simplification that neglects the effects of turbulence and mixing, which are caused both by daily surface heating and cooling and by the evaporation of water. Both effects disturb the logarithmic wind speed profile and change z_0 over short space and time scales.

Settling Speed of Particles in Air

Deposition of wind-transported sediment occurs when lift forces can no longer keep the sediment airborne, that is, when wind speed and the speed of air in turbulent atmospheric eddies fall below those needed to suspend particles. Particle fall speeds depend on grain diameter, a relationship described by Stokes' Law, named after George Gabriel Stokes, who proposed it in 1851:

$$S_s = 2r^2(\rho_p - \rho_f)g/9\mu_f \qquad \text{eq. 10.1}$$

Stokes' Law relates the settling speed (S_s) of a particle of radius r in a fluid to the density (ρ_f in general, ρ_a for air and ρ_w for water, specifically) and dynamic viscosity (μ_f) of the fluid, the acceleration of gravity (g), and the density of the particle (ρ_p). Stokes' Law is applicable to settling in laminar flow conditions, not the turbulent flow conditions



Air, a moving fluid, interacts with boundaries such as the ground surface. This frictional resistance means that near the ground, the wind velocity decreases to zero. Above the ground, wind speed increases. Thus, if grains can be lofted into the flow by impacts of other grains or by turbulent eddies, they will move more rapidly. The y-axis intercept of the height /speed curve, $\mathbf{z_0}$, reflects surface roughness and is known as the **roughness length** in the Karman/Prandtl model for air speed. Rough surfaces have a higher $\mathbf{z_0}$ than smooth surfaces.

FIGURE 10.3 Relationship of Wind Speed and Height Above Earth's Surface. Air speed increases as the logarithm of the height above Earth's surface, with roughness of the underlying surface controlling the value of z_0.

often encountered in nature, particularly near rough surfaces. Nevertheless, Stokes' Law provides a useful way to consider the behavior of very fine particles in a fluid such as air (see the Worked Problem).

Spatial Distribution of Wind-Driven Geomorphic Processes

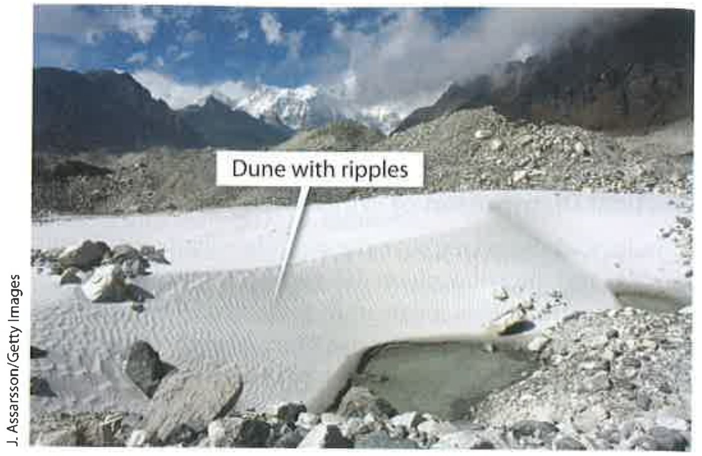
Wind and wind-carried sediments are present around the globe, but wind is a major or dominant force in landscape modification and sediment transport only in certain geomorphic environments, such as deserts, shorelines, the margins of ice sheets, and areas cleared of vegetation by agriculture or military operations. On other planets, such as Mars, the absence of vegetation and of liquid water allows wind to be a dominant driver of geomorphic change planetwide.

Conceptually, one can consider what has been termed the **sediment state** of a geomorphic system. In the case of aeolian geomorphic systems, defining the sediment state requires (1) identifying the source of wind-transportable sediment, (2) determining its availability for transport, and (3) considering the wind energy available to move the material. In most cases, sufficient wind energy is available to move sediment; the limiting factors are a source of sediment containing wind-transportable grain sizes and the availability of that sediment to move. Sediment availability is modulated by vegetation, moisture content, and the physical nature of the material at Earth's surface. Vegetated, cohesive, moist soils are too resistant to be moved at common wind speeds. In this context, it is easy to see why aeolian processes dominate in areas with loose, dry soils, scarce vegetation, and high wind speeds.

Wind can also be a major process in shaping coastal landscapes. Wind speeds tend to be higher at the coast than inland because the water surface is less rough than the land and because there are thermal contrasts between land and water. The heating and cooling of the land in daily cycles drives regular patterns of onshore and offshore winds. The abundant supply of fine sediment (sand and silt) from beaches and the longshore drift system (see Chapter 8) provide material for wind transport. Salt spray and disturbance from storms tend to limit the continuity and longevity of near-shore vegetation, episodically opening areas of bare soil to erosion by wind.

Landscapes at the margins of ice sheets are frequently affected by wind. Abundant unconsolidated sediment, delivered to the ice margin by streams running over and under the ice, is easily moved by wind once the sediment dries because newly deglaciated areas are unvegetated. Prolonged exposure of such sediment often leaves behind a lag of gravel and cobbles too large for prevailing wind speeds to transport. On glacial outwash plains, meltwater pulses supply fresh sediment each year, sediment that, when reworked, forms the dunes and deposits of wind-transported sediment sand and silt that are common near glacial margins and outwash streams [Photograph 10.4]. The contrast in temperature between large ice sheets and the surrounding terrain can generate **katabatic winds** as cold, dense air descends off the ice. Such winds can kick up large plumes of dust from sparsely vegetated outwash plains [Photograph 10.5].

Areas altered by human activities are frequently modified by wind because disturbance removes anchoring vegetation and disturbs soil structure. Agriculture, construction, and military activities all disturb soil and provide a ready source of material for wind to transport [Photograph 10.6]. Wind can strip fertile topsoil. This fine sediment, lofted into the air from bare ground, fouls internal combustion engines, reduces visibility, and can have significant health effects.



J. Assarsson/Getty Images

PHOTOGRAPH 10.4 Wind-Transported Sediment at Glacial Margins. Aeolian activity is frequent and widespread near glacial margins. Here, a dune of white rippled sand lies on the ablating margin of Nepal's Ngozumpa glacier in the Himalaya.

© Arctic-Images/Corbis

PHOTOGRAPH 10.5 Wind Erosion Along Glacial Outwash Stream. Dust rises in the wind from Myrdalssandur outwash plain around a stream that drains a small ice cap on the southeastern coast of Iceland.

(a)

Bob Strong/Reuters/Landov

(b)

AP Photo/Gene Blythe

PHOTOGRAPH 10.6 Human Activity and Wind. Human activities disturb the ground surface, allowing wind to erode and transport sediment. (a) U.S. Army soldiers shield themselves from airborne dust kicked up from bare ground by a Medevac helicopter taking off outside of Kandahär, Afghanistan. (b) Farmer plowing a bare field raises a cloud of dust that is carried off by the wind.

Aeolian Processes

The geomorphic effects of wind can be considered in terms of disturbance, erosion, transport, and deposition—all related to the sediment state described above. The ability of wind to disturb vegetation communities and erode material depends on both the strength of the wind and substrate resistance (which is related to climate and vegetation, as well as soil properties and moisture content). Transport and deposition of sediment by wind depend on wind speed and its variability over time and space.

Disturbance

Strong winds, primarily during and just after storms, commonly disturb Earth's surface and thus catalyze other surface processes, particularly on hillslopes, the effects of which we consider explicitly elsewhere in the book. Of particular importance is the effect of wind on trees. High winds topple both single trees and whole sections of forests, especially on and near steep ridgelines where wind speeds are generally highest. When trees fall, entire root wads are ripped from the ground, and there is net downslope transport of regolith. This **wind throw** mixes (bioturbates) soils, triggers mass movements, and facilitates bedrock weathering (Photograph 5.6). Storm-induced floods also provide a source of unconsolidated sediment that is easily eroded and transported by wind. Deposits of fine-grained overbank flood sediment are particularly susceptible to wind erosion before they revegetate.

Humans are major agents of disturbance, cutting forests, tilling fields, disturbing fragile desert soil crusts, and siphoning off water supplies of lakes in internally drained basins, which then shrink, facilitating wind erosion of the dry lakebeds [Photograph 10.7]. The result of anthropogenic disturbance is more dust transport in the atmosphere and, in some places, significant wind erosion of barren areas. Human-induced climate change could greatly decrease Earth's vegetation cover through increased droughts, more frequent forest fires, and the die-back of trees from diseases and insects spreading poleward in a warming climate. Warming and drying of the North American Midwest in response to global warming (as predicted by climate models) could cause reactivation and erosion of currently stable aeolian deposits if the vegetation dies back.

P. Bierman

PHOTOGRAPH 10.7 Dry Lakebed. The white dusty playa is all that remains of Owens Lake in southern California after a century of water withdrawals from the watershed by Los Angeles Water and Power. Here, dust blows off the dry lakebed in a spring dust storm.

Erosion

Wind exerts forces on earth materials as it moves over them. Such forces include both lifting and shearing components. Critical to understanding the mobilization of granular, noncohesive sediment by wind is the difference between the **fluid threshold** and the **impact threshold.** The fluid threshold is the wind speed needed to erode material when no sediment is in motion. If the force exerted by the wind exceeds the resisting force of the substrate material (frictional strength, particle mass, or cohesion), sediment will be entrained and erosion will begin [**Figure 10.4**]. Fine-grained sediment, with a grain size between a few tens and a few hundred micrometers (thousandths of a millimeter), is the optimal size for erosion and transport by wind as indicated by the wind-speed minimum in the fluid threshold curve in Figure 10.4. The wind-speed minimum arises because grains smaller than about 100 μm

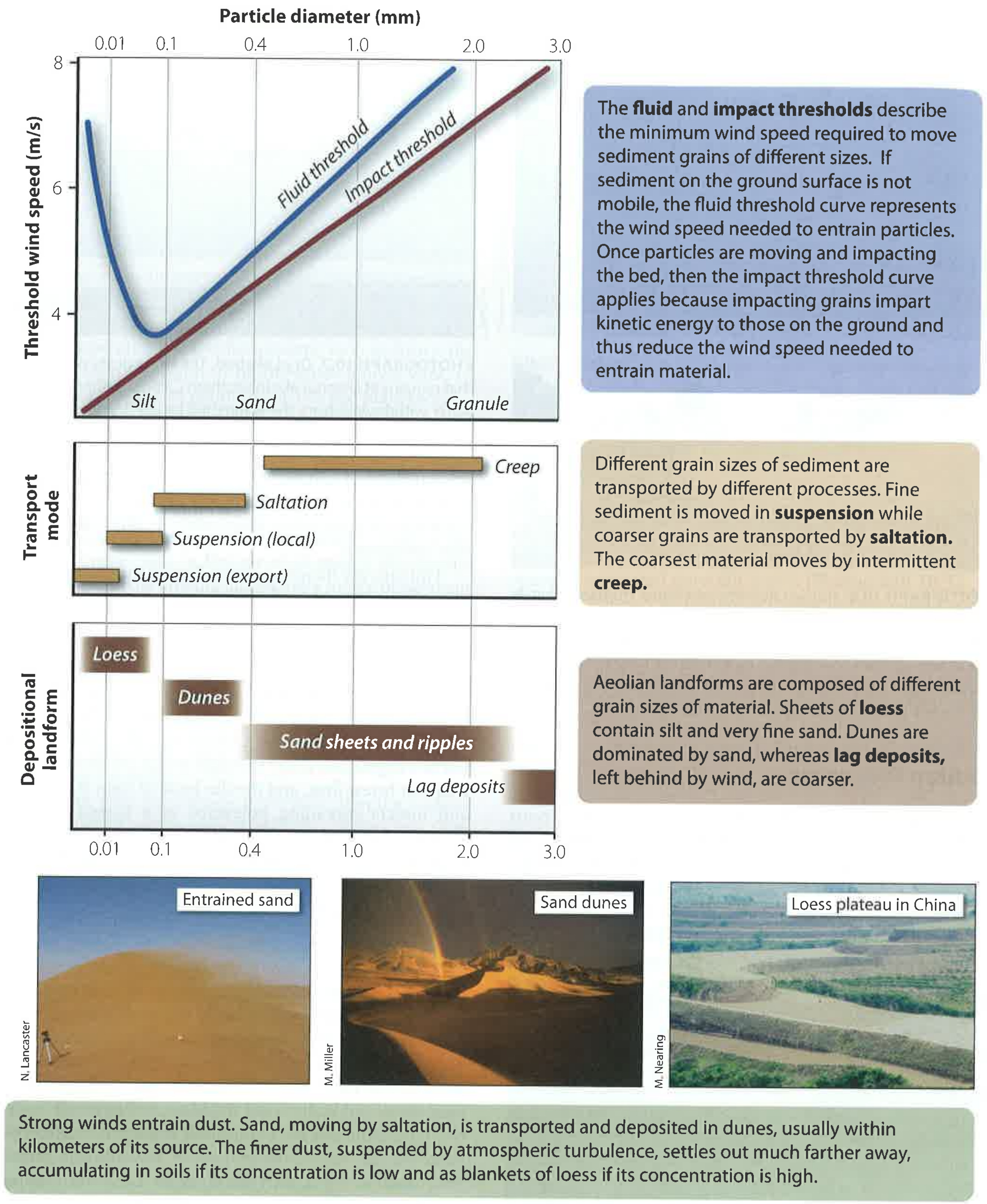


FIGURE 10.4 Wind Speeds Required to Move Sediment. Different wind speeds are required to initiate movement of materials of different grain sizes by wind. Different aeolian landforms are made of grains of different sizes.

(0.1 mm) are resistant to erosion because they are cohesive and because larger grain sizes have greater mass per grain and thus require higher wind speed to move.

The impact threshold is the wind speed required to erode sediment once some sediment is already in motion. Fluid-threshold and impact-threshold wind speeds are different; the impact threshold is always lower. This is easy to remember if one considers the physics of the process. Moving sediment impacts the ground surface, transferring some kinetic energy to surface grains; thus, the kinetic energy from wind necessary to mobilize sediment is reduced by the amount of energy already transferred to the particles by impact. For example, silt (wind-blown sediment of size <63 μm, known as loess) rarely gets mobilized without prior mobilization of fine sand, grains >125 μm. Once sand impacts and abrades a silt-rich ground surface, the critical wind speed for mobilizing the silt is lowered from the fluid-threshold value to the impact-threshold value, which, in the case of small grains, is a manyfold difference in speed (Figure 10.4).

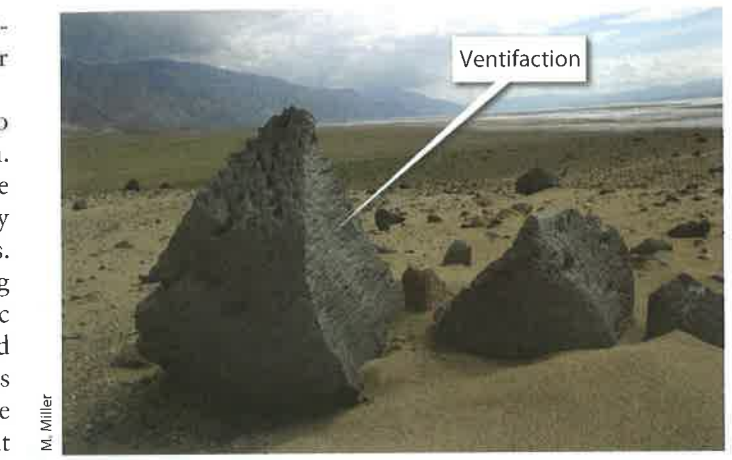
Erosion of granular, noncohesive materials requires a sufficient lift force to remove grains from the bed; thus, in most wind regimes, transport is usually limited to sand-sized and smaller grains. Under the range of wind speeds typical above Earth's surface, coarse-grained granular material does not move because air, being a low-viscosity, low-density fluid, generates insufficient lift forces and momentum transfer.

Cohesive materials are generally resistant to direct wind scour because shear and lift forces generated at typical wind speeds are insufficient to overcome the cohesive strength and detach grains. For soils, apparent cohesion (see Chapter 5) can be provided by vegetation and root structures as well as by biologic crusts and the binding of soil particles by clay and soil moisture (see Photograph 10.3). Damp or water-saturated granular material is less easily eroded by wind. The **surface tension** provided by interstitial water (a type of apparent cohesion) resists aeolian lift forces.

In the southwestern United States, the development of Bt (clay-rich) and Bk (carbonate-rich) horizons during periods of several thousand years between times of active aeolian sediment transport appears to strengthen the soil. The additional cohesion provided by interstitial soil clay and soil carbonate plays a key role in limiting erosion of the previously deposited aeolian sediment.

Moving air often carries sediment, and the impacts of this sediment on cohesive materials can cause erosion by **abrasion.** Such abrasion creates wind polish on surfaces, frosts glass in sandstorms, and creates ventifacts, or wind-eroded rocks [**Photograph 10.8**]. It appears that maximum rates of aeolian abrasion occur within tens of centimeters of the ground surface, reflecting the net influence of the vertical distributions of both airborne-sediment concentration and wind speed.

Rates of aeolian erosion of bedrock are difficult to quantify and as such are poorly constrained in general. Reported global average rates of aeolian erosion range from 0.25 to >10 m/My, depending on assumptions used in the calculation. Rates for specific regions are higher, some in excess of 20 m/My. Point measurements suggest that short-term erosion rates can be higher yet, up to 1 mm in 15 years, which is about 70 m/My.

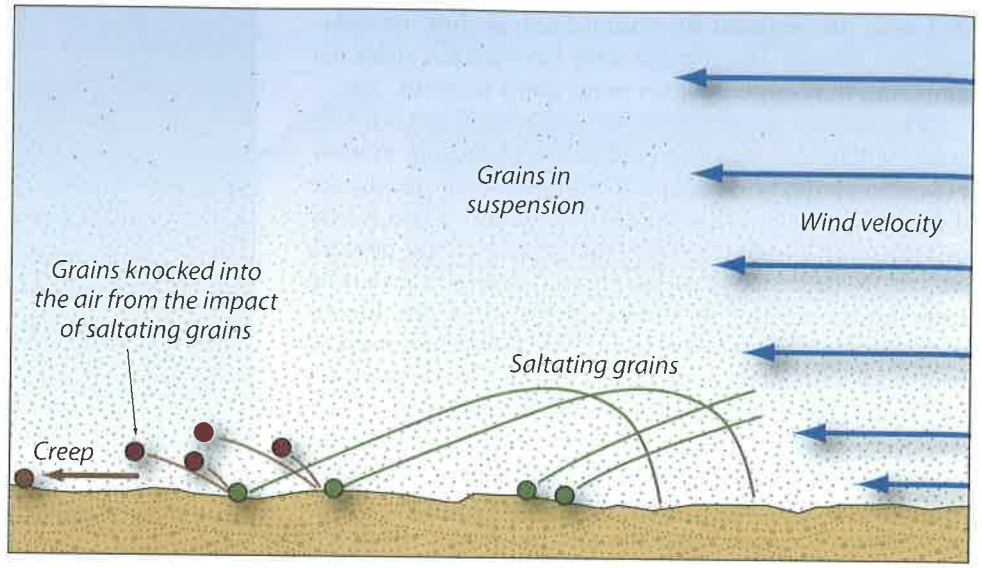


PHOTOGRAPH 10.8 Basaltic Ventifacts. This large boulder in Death Valley, California, has been eroded by wind and is about a meter wide.

Sediment Transport

Once detached, clay-, silt- and sand-sized material can be moved by wind. Similar to sediment transport in water, sediment moving in air can take different paths, depending on its grain size. These paths reflect the physical balance between the **settling speed** (eq. 10.1) and the lift and shear forces. Wind transport is typically partitioned into three processes: **suspension, saltation,** and **creep** [**Figure 10.5**].

Wind can transport fine-grained sediment in suspension long distances, hundreds to thousands of kilometers [**Photograph 10.9**]. Such sediment settles out downwind of the source, which is generally an arid or semi-arid region with minimal vegetative cover [**Figure 10.6**]. Dust storms, so famous from the Dust Bowl years of the 1930s in North America and today across North Africa and central Asia, are the most dramatic example of wind-suspended sediment. During the Dust Bowl era, dust from agricultural fields on the North American Great Plains rained out on East Coast cities, bringing an eerie darkness to midday. Such dust storms are not a thing of the past. In 2009, red dust from the center of Australia turned the Sydney sky orange at midday [**Photograph 10.10**]. Dust storms, which transport large amounts of fine-grained sediment long distances, are most common in semi-arid climates where sufficient water is available to weather rock to fine grain sizes but vegetation cover, which stabilizes soil surfaces and prevents wind erosion, is scarce. A number of studies show that dust is delivered to Earth's surface by rain associated with dust storms. One can easily verify this phenomenon in arid and semi-arid regions. On those days when only enough rain falls to leave a few raindrops on your



Wind transports grains by three different processes. Small grains are kept in **suspension** by turbulence. Larger grains are dislodged from the surface by impacts and **saltate,** moving downwind in ballistic trajectories. The largest grains move by **creep,** pushed forward by impacting grains and rolled forward by the viscous drag of moving air.

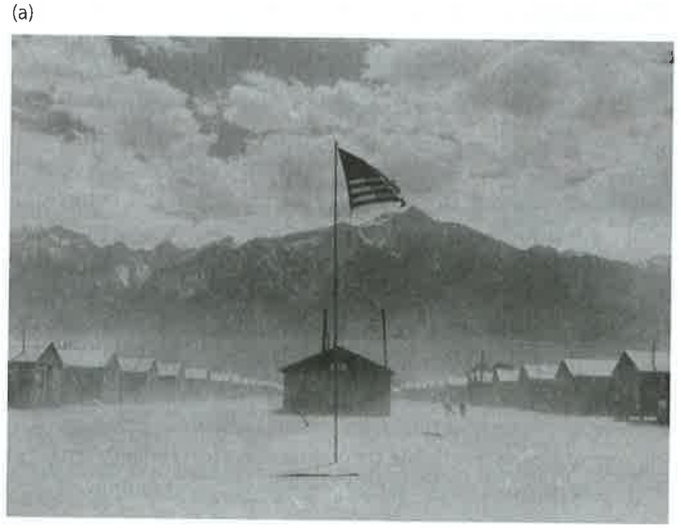
FIGURE 10.5 Processes of Aeolian Sediment Transport. Wind transport of sediment occurs by suspension, saltation, and creep.

windshield but not enough to completely wet and wash the window, let the drops dry and the dust they carried becomes evident.

Saltation is the episodic or hopping movement of particles up from the ground surface and back down over short distances. Most particles are lifted by wind only centimeters to decimeters above the ground, move forward with the wind, and then quickly fall back under the influence of gravity. Because saltating grains cannot rise far above the ground surface, the effective erosion zone for wind is very close to the ground surface as shown by the scalloped bases of telephone poles and fence posts eroded by abrasion and by deposition of wind-carried sediment [**Photograph 10.11**].

Wind creep is the movement of particles that are too large to be lifted by the wind. Some particle movement may be induced by the pressure difference between the

(a)

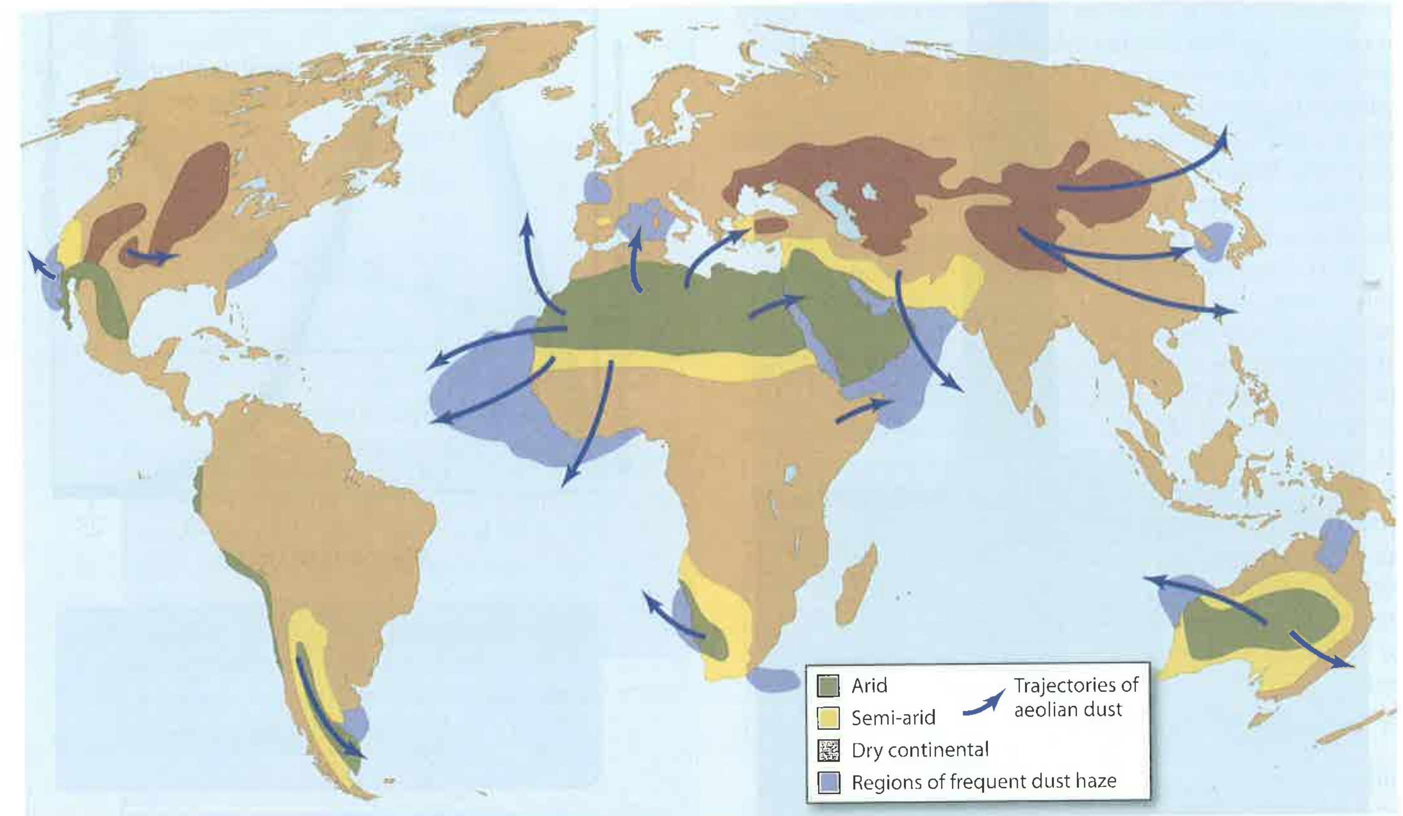


D. Lange

(b)

Tony Freeman/Science Source

PHOTOGRAPH 10.9 Dust Storms. (a) In the 1940s, dust blows through the War Relocation Authority Center, Manzanar, California, to which U.S. citizens of Japanese ancestry were deported during World War II. This camp was in the shadow of the Sierra Nevada north of Lone Pine, California. The large clouds of dust are the result of humans disturbing the desert surface, although dust storms can occur in the absence of human disturbance. (b) Large cloud of windblown dust rolls into Yuma, Arizona.



There are many sources of dust in the world—all of which are at least seasonally dry lands. This dust is transported by the prevailing winds and deposited as **loess** on land and contributes to the accumulation of fine sediment on the abyssal plains of the oceans.

FIGURE 10.6 Airborne Dust Sources and Trajectories. The most important sources of airborne dust are drylands. Dust is carried by prevailing winds, the direction of which is determined by overall atmospheric circulation.

R. Lahiff

PHOTOGRAPH 10.10 Dust Storm. The North Sydney Olympic Swimming Pool and the Harbor Bridge against a backdrop of dust in September 2009, Sydney, Australia. More than 1000 km of the eastern coastline of Australia was affected by the dust, which was the result of gale-force winds blowing southeast from the drought-stricken Northern Territory.

upwind and downwind sides of the particle. In general, creeping particles, although too big to be ejected from the ground surface, are rolled and pushed along the surface by the energy imparted to them by other impacting grains.

The collision between falling particles and those on the ground is important because it transfers energy and thus helps drive creep and eject different particles into the flow. Turbulence in the air results in vortices and gusts of wind that impact the ground surface, loosening grains and initiating aeolian sediment transport. Active saltation lowers the entrainment speed such that slower winds become more effective agents of erosion. Remember the difference between fluid threshold and impact threshold (Figure 10.4). Once saltation begins (when wind speed exceeds the fluid threshold), it is easier to sustain even if wind speed drops a bit (as long as the wind speed remains above the impact threshold).

Sediment transport by wind is a threshold phenomenon with significant feedbacks. At low wind speeds, nothing moves. When the fluid threshold is crossed and motion begins, saltating grains both dislodge other grains and abrade

B. Hallet

PHOTOGRAPH 10.11 Wind Transport Profile. This telephone pole shows differential wind transport of material in the San Joaquin Valley after a wind storm in 1977 that stripped the region of much fertile soil in only ~25 hours. More mud is caked on the lower portion of the pole, nearer to the ground where transport of material is greatest. The dust was turned to mud in this area because it was blown across an irrigation canal and picked up moisture.

cohesive material—moving grains keep the system in action once action begins. Thus, a small increase in wind speed can translate into a very large increase in aeolian sediment transport. In other words, the rate of sand transport increases nonlinearly with wind speed. If one multiplies the annual record of wind speed with the sediment transport rate as a function of wind speed, it becomes clear that most sand is transported by moderate winds, those moving about 15 m/s (54 km/h) [Figure 10.7]. This transport maximum reflects a balance between the increasing sediment transport rate as wind speed increases and the relative rarity of very strong winds.

From the volume of fine-grained sediment delivered to the oceans, it appears that rates of aeolian deposition increased significantly at the onset of major Northern Hemisphere glaciation, about 2.7 million years ago. This increase likely reflects both the large amount of fine-grained sediment delivered from glaciers as well as increased sediment availability because the climate on average grew colder and drier, and Earth's surface became less well vegetated. Faster wind speeds (responding to increased atmospheric pressure gradients) may have also contributed to increasing sediment transport by wind during glacial periods.

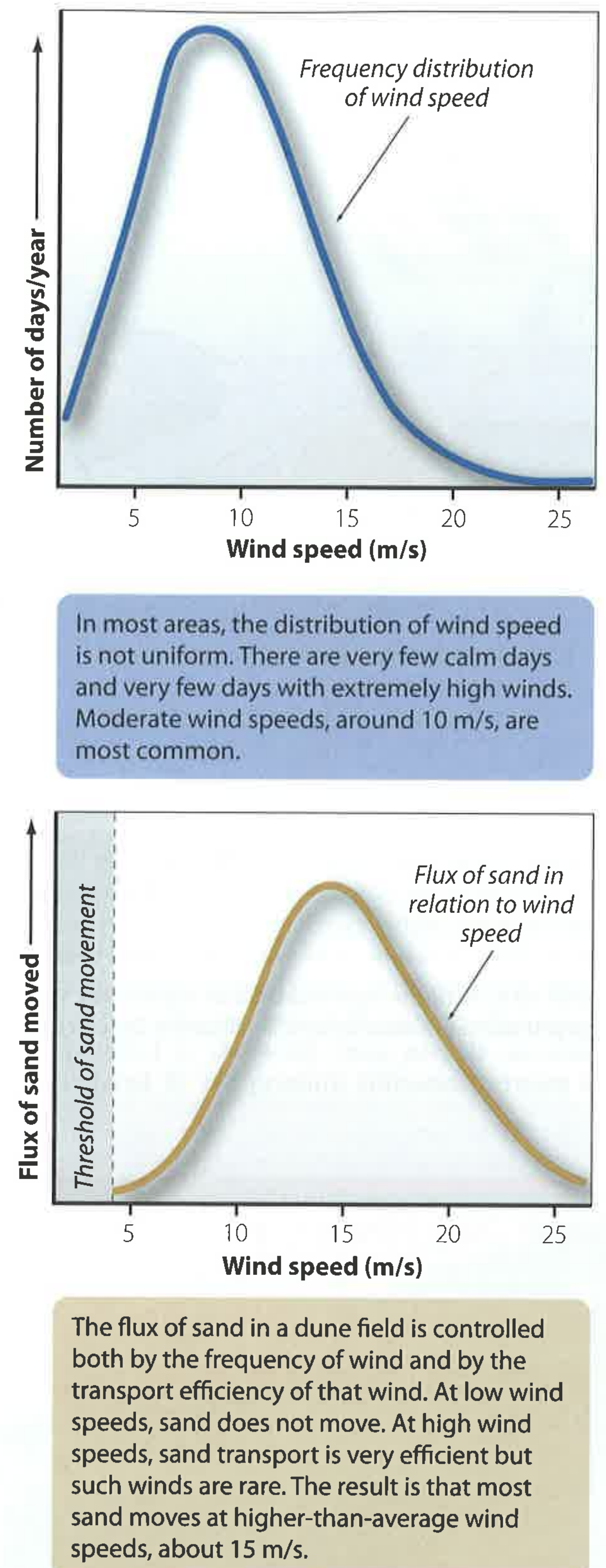


FIGURE 10.7 Wind Speed and Aeolian Transport. Most aeolian sediment is transported by moderate-strength winds. Low-speed wind transports no sediment until a distinct mobility threshold is crossed.

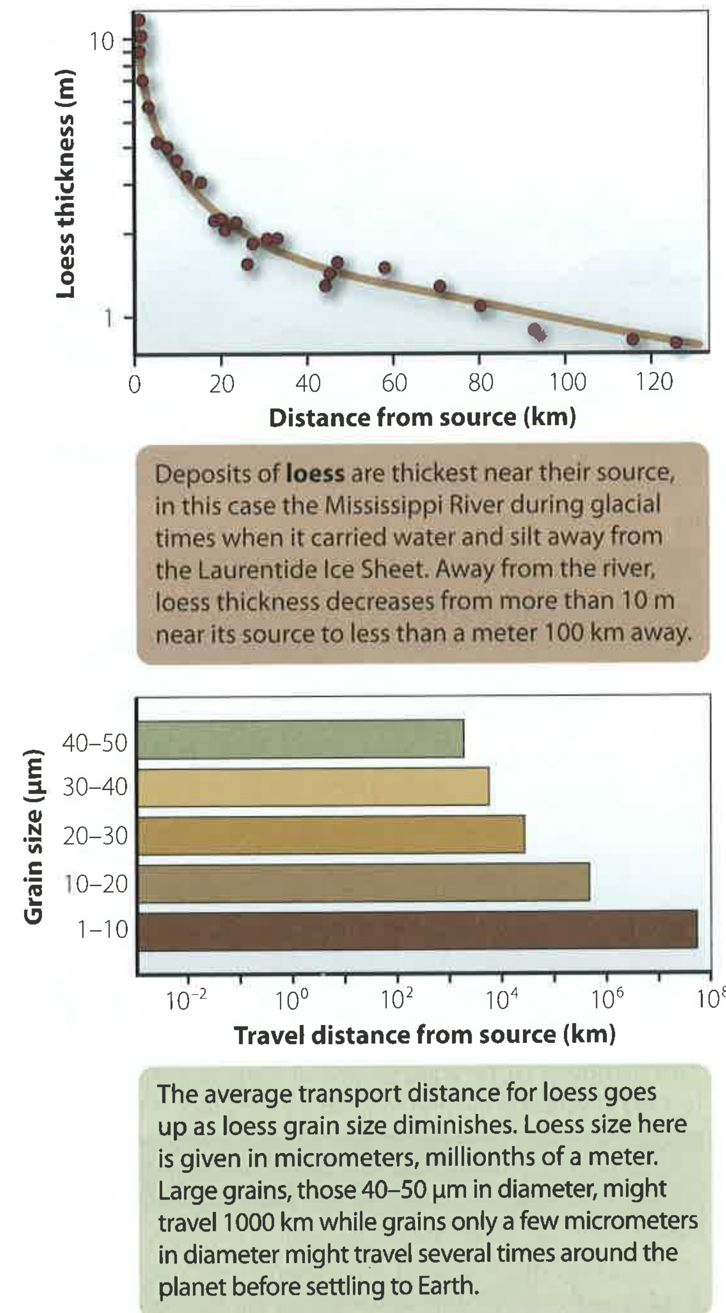


FIGURE 10.8 Wind Transport of Loess. Loess thickness and grain size changes downwind from the source. Grain size and thickness of loess decreases away from the source as larger-diameter grains settle more quickly than smaller grains. [Adapted from Livingston and Warren (1996).]

Deposition

Aeolian sediment is deposited when the settling speed of particles exceeds the lift forces provided by turbulent flow. From Stokes' Law (eq. 10.1), we see that the settling speed is related to the square of the particle radius; thus, large particles will fall much more quickly through fluids than small ones. For aeolian transport, this relationship implies that fine-grained material can stay aloft longer than coarse material. Field data support this theory-based assertion. For example, the grain size of wind-deposited sediment reflects downwind sorting as the coarser particles settle out closer to the source than the finer particles [Figure 10.8].

Surface roughness is also important for determining where aeolian sediment will be deposited. Rough surfaces will slow moving air, reducing lift forces and causing sediment to be deposited. This effect is well demonstrated by coppice deposits of sand and silt that form adjacent to shrubs (roughness elements) in the desert [Photograph 10.12]; the shrubs disturb the air flow and sediment settles out in the low-wind-speed region downwind of the plant. Bouldery alluvial and debris-flow deposits as well as lava flows can be very rough, locally decreasing near-surface wind velocities and particle lifting forces; thus, these surfaces can function as effective aeolian sediment traps, leading over time to surface burial and, in some cases, the development of desert pavements (see Digging Deeper). Wind-formed features, like dunes, also contribute to surface roughness.

There are several reasons why wind-deposited sediment, on the whole, is better sorted than sediment deposited by moving water. Most important, the size distribution of material transportable by wind is limited: silt, sand, and in extreme cases very fine gravel that slowly creeps or rolls in the highest winds. For sand-sized material, the settling speed is high enough that transport is limited to saltation, an inefficient means by which to move sediment long distances. Silt, because of its low Stokes settling speed, is carried in suspension. With the gravel left behind and transport speeds of suspended silt being much higher than those of saltating sand, it is easy to see how sand dunes and dust deposits derived from the same source can be both very well-sorted and separated by kilometers or more.

P. Bierman

PHOTOGRAPH 10.12 Coppice Dune. This coppice dune behind a shrub on a dry lakebed (pan) at Sossusvlei in the Namibian Sand Sea (erg) is about 3 m long. Star dunes are in the distance.

Aeolian Features, Landforms, and Deposits

The distribution of both depositional and erosional aeolian landforms is nonuniform and reflects the importance of numerous covarying factors including wind speed, sediment moisture content, substrate erodibility, the area available to accommodate aeolian sediment, surface roughness, and vegetation density. Many landforms of aeolian deposition are also landforms of aeolian sediment movement or translation, meaning that they are temporary storage reservoirs of sediment that are constantly being remolded as sediment is transported through them.

Aeolian Erosional Features and Landforms

Ventifacts are wind-eroded rocks on the scale of decimeters to meters found in a variety of locations. They are prevalent in relatively arid regions or in regions that were arid in the past. Common in mid- and low-latitude deserts, ventifacts are also found in polar regions, particularly along valley bottoms occupied by sediment-loaded outwash streams. Presumably, katabatic winds from nearby glaciers suspended outwash sand and silt that abraded the ventifacts.

Ventifacts are often polished, faceted, and may have pits or **flutes** (elongated pits) on their surfaces (Photograph 10.8). These distinctive surface features suggest that ventifacts formed through abrasion of the immobile surface by saltating or suspended material (sand and silt). Most ventifacts are low to the ground, consistent with high sediment concentrations found in air near the ground surface. Faceting is more difficult to explain and may reflect the influence of different wind directions or the movement of the clasts over time. Such movement could result from frost action in cold regions or shrink-swell behavior in desert soils. The long axis of flutes eroded into rock is parallel to the predominant wind direction; thus, if the clast has not moved, the orientation of flutes can be used to estimate the direction of the strongest winds in the past, those capable of eroding rock.

© Mike P. Shepherd/Alamy

PHOTOGRAPH 10.13 Yardang. Yardang eroded into soft, fine grain sedimentary rock in Tunisia. Wind blew from left to right.

(a)

Georg Gerster/Science Source

(b)

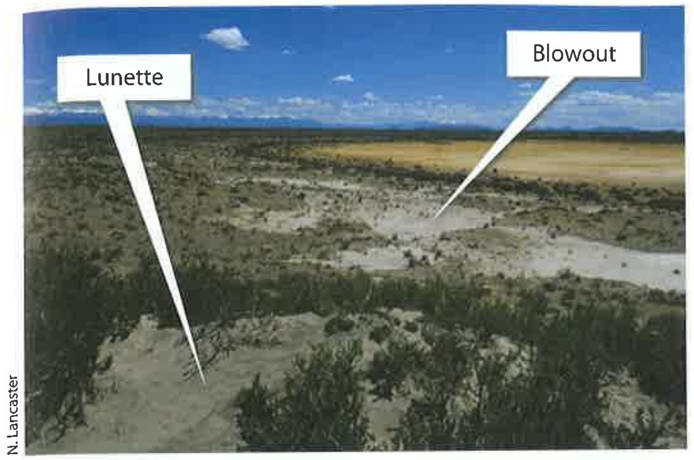
© NASA/Corbis

PHOTOGRAPH 10.14 Wind Erosion on Earth and Mars. (a) Field of yardangs cut into soft, sedimentary rock in the Farafra Depression, Egypt's Western Desert. Wind blew from right to left. (b) Grooves sculpted by wind-blown sand near Olympus Mons on Mars. The image shows an area that is about 20 km wide.

Yardangs (from Turkish for "steep bank") are streamlined, positive-relief abrasional forms cut into bedrock or other cohesive earth materials by wind-driven sediment; they are much larger than ventifacts, ranging in size from meters to hundreds of meters in length and have a blunt upwind side and taper downwind like an inverted ship's hull [**Photograph 10.13**]. Yardangs are most likely formed where the prevailing wind is unidirectional. The long axis of a yardang is oriented in the same direction as the wind that eroded the feature. Fields of yardangs are found in many mid- and low-latitude deserts such as the Sahara [**Photograph 10.14a**]. Yardangs and unusual elongate erosional grooves (negative-relief features) have also been identified on Mars using remote sensing [**Photograph 10.14b**], confirming that wind is or was an active geomorphic process eroding the surface of Mars.

Blowouts and **deflation hollows** are areas where sediment has been removed by wind, forming a shallow pit or depression. They usually extend no deeper than the water table, where apparent cohesion of the sediment prevents further erosion. Blowouts are most common in areas where sediment is weak, granular, or poorly cemented. For example, blowouts are common in dry lakebeds and in coastal dune fields between vegetated areas. Blowouts are also common in vegetation-stabilized sand sheets and dunes. Sometimes, small dunes composed of fine-grained sediment (termed **lunettes**) form immediately downwind of blowouts [**Photograph 10.15**].

Pavements, concentrations of interlocking clasts on desert surfaces, were once thought to form by deflation, or the selective winnowing and removal of fine sediment by wind [**Photograph 10.16**]. They are common on gently sloping surfaces in arid regions, and are especially well-developed on the low-gradient distal sections of alluvial fans. Although deflation can leave a residual lag of clasts, evidence collected since the 1980s suggests that many pavements are born at the surface and probably result from the gradual incorporation of wind-deposited silt over time (see Digging Deeper).



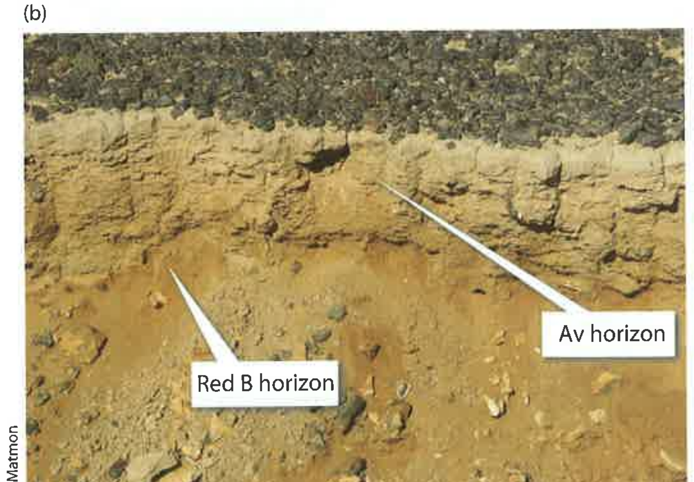
N. Lancaster

PHOTOGRAPH 10.15 Lunette and Blowout. Small lunette in Great Sand Dunes, Colorado, with larger blowout in the distance. The blowout is the source of sand in the lunette. Shrubs provide scale.

(a)

D. Trent

(b)



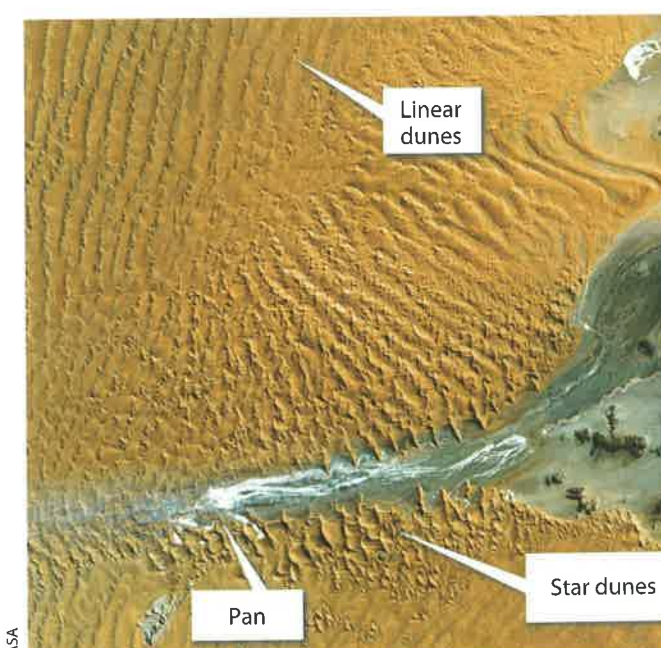
A. Matmon

PHOTOGRAPH 10.16 Desert Pavements. Well-developed desert pavements have a single layer of interlocking, heavily rock-varnished clasts underlain by a stone-free, columnar, fine-grained Av horizon and a reddened B horizon. (a) View of pavement surface in Panamint Valley, California. Rock hammer is included for scale. (b) Cross-section view of a desert pavement in the Negev Desert, Israel, underlain by a 15-cm-thick Av horizon.

Aeolian Transport Features and Landforms

Landscapes dominated by aeolian processes contain a variety of landforms and features indicative of sediment transport by wind. At all scales, these features are composed predominately of granular, noncohesive material, primarily sand.

Regional accumulations of sand, known as sand seas or **ergs** (from the Arabic for "dune field") are the largest aeolian features [**Photograph 10.17**]. Ergs, which can cover



NASA

PHOTOGRAPH 10.17 Sand Sea. Namibian Sand Sea (erg) in the central Namibian desert is bordered by rocky mountains to the east and the coast to the west. The ephemeral Tsauchab River ends in the sand sea, its waters evaporating in the pan, or dry lakebed. There are both linear and star dunes. Width of photograph is about 75 km.

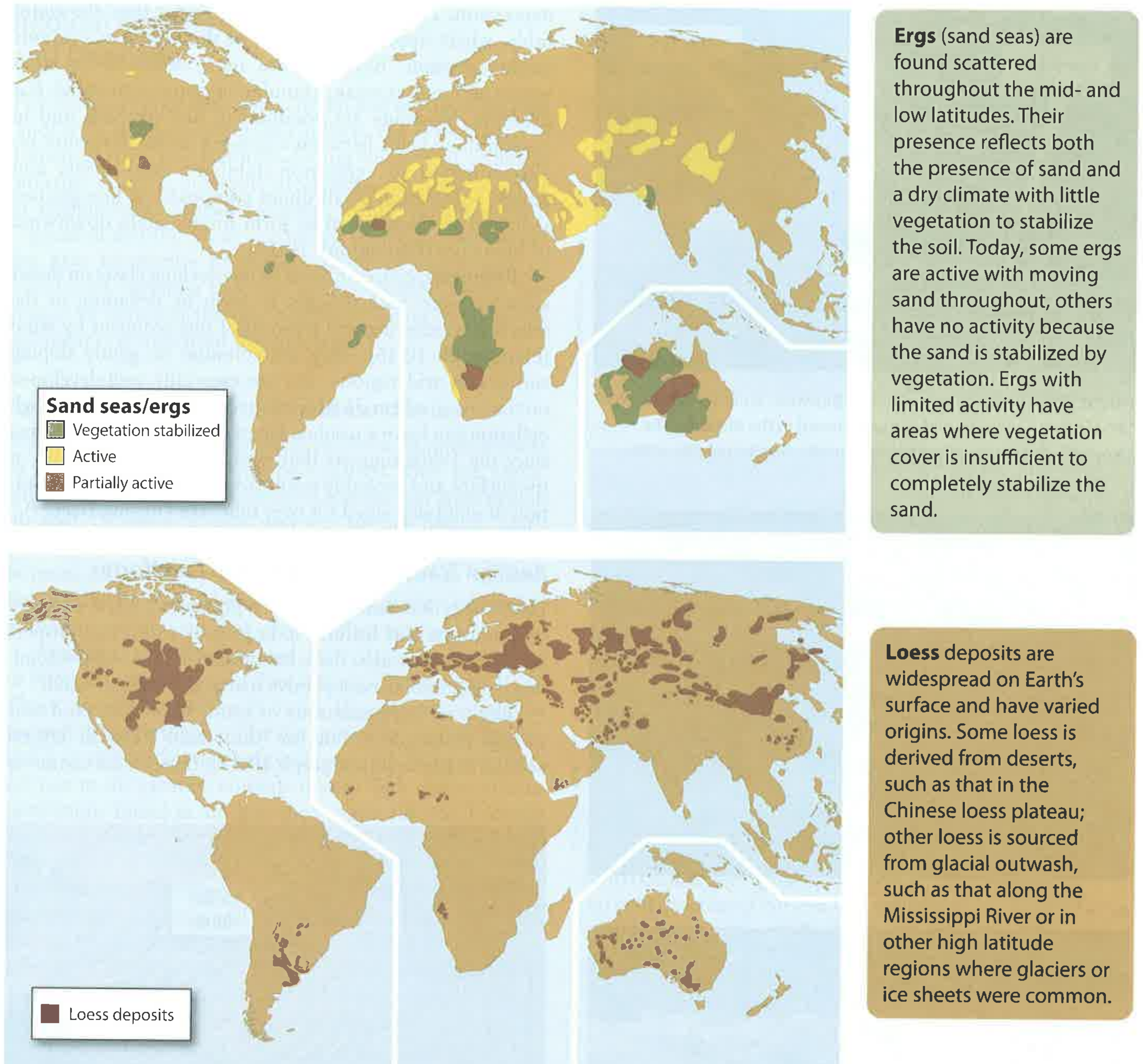


FIGURE 10.9 Global Distribution of Ergs and Loess. Ergs are most common in dry, low- and mid-latitude locations with little vegetation. Accumulations of loess are found downwind of dust sources including deserts and the locations of former ice sheets. [Adapted from Thomas (1989) and Hugget (2003).]

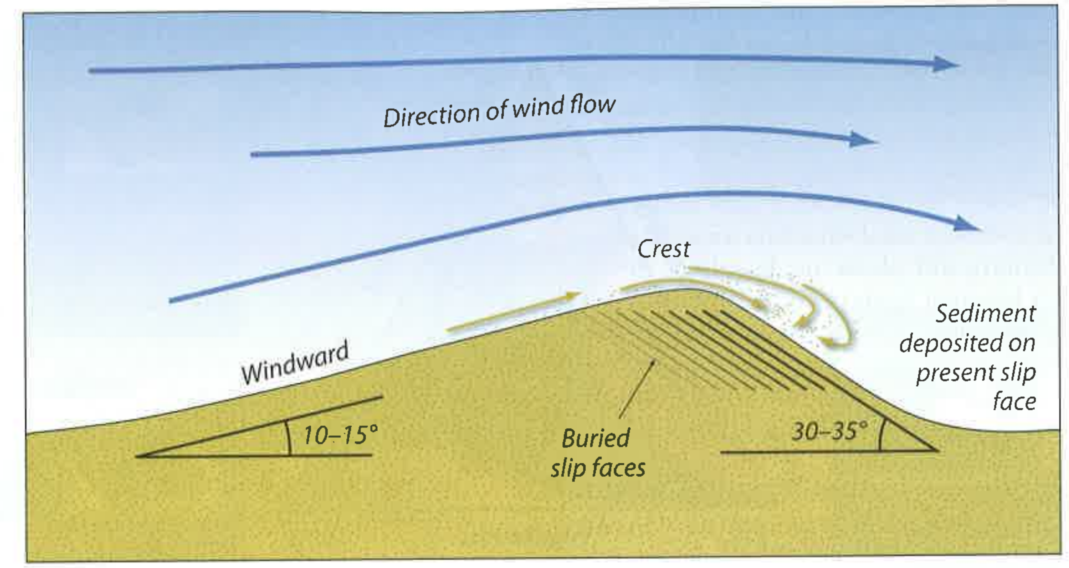
thousands to hundreds of thousands of square kilometers, contain sand derived from either longshore drift along the coast or from direct deposition by rivers. Most active ergs are in arid and semi-arid regions and many are at or near the 30° latitude bands [**Figure 10.9**].

Relict ergs are common in areas that were either drier (less vegetation) or had greater sediment supplies in the past when climate conditions were different. For example, the Sand Hills of Nebraska in central North America have sufficient moisture in today's climate regime to retain a cover of stabilizing vegetation, but were an active erg during drier times in the Pleistocene and Holocene. Erg reactivation does occur, either from disturbance, such as the removal of vegetation, or from climate change when drying causes vegetation to die off. Ergs form over multiple cycles of activity. Optical luminescence dating of cores collected from ergs shows that sand has moved during different periods in the past.

At a smaller scale, and often located within ergs, are **dunes.** Dunes have many different forms, which can be interpreted to reflect different sand-transport processes and boundary conditions. Lee-slope (or **slip-face**) avalanching is common to all dune types [**Figure 10.10** and **Photograph 10.18**]. A fundamental categorization considers whether the dune is associated with (anchored to) a topographic feature or whether it is free to move across the landscape. Examples of **anchored dunes** include those downwind of topographic obstructions and vegetation (Photograph 10.12) as well as **climbing dunes** or sand ramps attached to cliffs and steep slopes. The orientation of active dunes reflects today's wind direction(s); by inference, the orientation of now-stabilized dunes reflects paleowind direction(s).

The creation and maintenance of both free and anchored dunes can be considered through the physics of sand transport. Creating a dune requires depositing sand that is intermittently in transport. Consider a patch of sand on an otherwise hard (elastic) substrate. If a saltating grain lands on the sand patch, more of its kinetic energy will be dissipated (by displacing other grains and imparting momentum to them) than if the grain bounced off the hard substrate. Over time, this contrast in behavior with impact causes small sand patches to grow as impacting sand grains lose energy and are trapped. Once a dune begins to form, sand accelerates over the low-gradient, upwind side, cascades over and flows down the downwind side before being dropped by the divergent, decelerating flow. Rates of dune movement downwind vary greatly; typical values appear to be tens of meters per year.

Free dunes develop independent of topography [**Photograph 10.19** and **Figure 10.11**]. The number and



Wind carries sediment up and over dunes. Grains **saltate** up the backslope of dunes and avalanche down the steeper slip face. The dune moves or progrades downwind, burying previous slip faces and producing cross-bedded sand deposits.

FIGURE 10.10 Dune Migration. Free dunes migrate as sand is blown from the windward (upwind) to leeward (downwind) side of the dune. [Adapted from Summerfield (1991).]


E.D. McKee / USGS

PHOTOGRAPH 10.18 Slip-face Avalanching. Gypsum sand avalanching down the slip face of a dune at White Sands, New Mexico.


L. Galuzzi

PHOTOGRAPH 10.19 Star Dune. Large star dune that developed and moved independent of topography in Sossusvlei region, Namib-Naukluft National Park, Namibia.

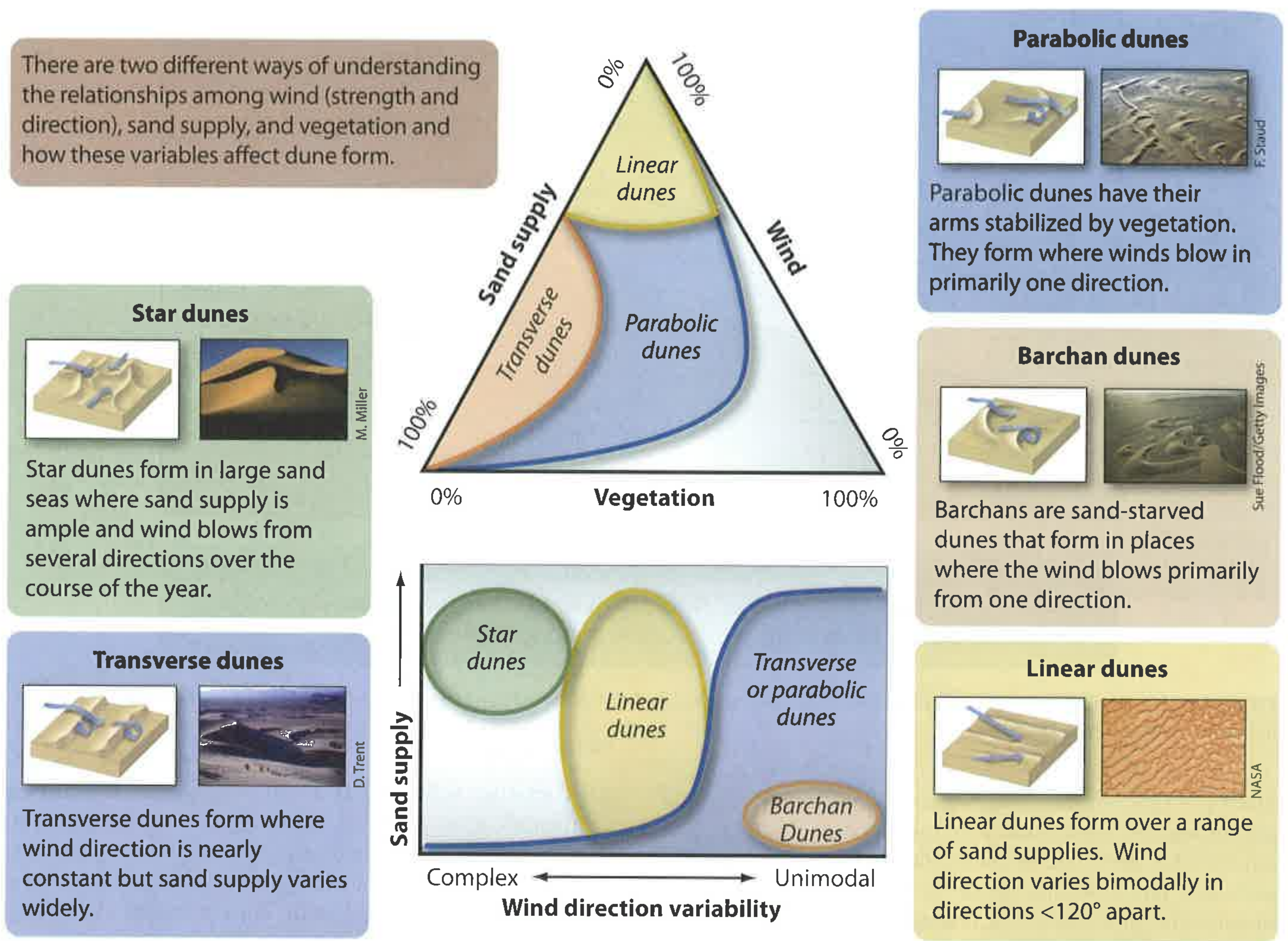


FIGURE 10.11 Dune Types. The morphology of sand dunes and the processes that control their shape and mobility reflect both sand supply and the variability of wind direction. [Adapted from Hack (1941) and Livingston and Warren (1996).]

orientation of slip faces are key to interpreting the process of dune formation and inferring the wind regime. Free dunes are categorized as transverse or linear. Sand transport is perpendicular to the crest of **transverse dunes** and parallel to the crest of **linear dunes** that have slip faces on both sides of the crest—active alternately as wind direction changes seasonally. **Star dunes** have slip faces oriented in several different directions; they are interpreted as reflecting dune development in an environment where wind direction changes seasonally, resulting in little net sand transport. Note that the key factor in the formation of star dunes is not the frequency of wind-direction changes, but that winds come from several different directions during the year.

There are two types of transverse dunes. Both form **crescentic ridges** in areas where there is little available sand and the wind blows predominately from one direction. The tips of **barchan dunes** move more rapidly downwind than the slower main body of the dune, presumably because there is less energy dissipation by loose sand at the tips on the firm desert surface than over the main part of the dune. In contrast, **parabolic dunes** have their upwind arms anchored by vegetation. Many parabolic dunes form in areas where the underlying sand is vegetated and unavailable for transport until the stabilizing vegetative cover is disturbed. When the vegetation is disturbed, parabolic dunes originate from **blowouts,** bowl-shaped, erosion pits (Photograph 10.15) formed where wind erodes a formerly stabilized sand surface.

Superimposed on these larger dunes are smaller **ripples,** ubiquitous asymmetric bedforms that cover dune surfaces [**Photograph 10.20**]. The upwind sides of ripples are gently sloping and the downwind slopes are generally steeper, like dunes. Ripples are ubiquitous in sandy areas without vegetation. Individually, ripples tend to be short-lived, their orientation adapting rapidly to changing wind direction. Sediment grain size appears to control the wavelength and height of ripples. Most ripples have wavelengths of centimeters to meters and heights of centimeters, and they are oriented perpendicular to the

PHOTOGRAPH 10.20 Ripples on Dunes. Ripples cover this large sand dune at the Great Sand Dunes National Monument, Colorado.

wind flow [**Photograph 10.21**]. Low slope angles for ripples, 2 to 7 degrees for stoss slopes and 2 to 10 degrees for lee slopes suggest that suspension rather than saltation and avalanching are the dominant sand-transport processes on these fine-scale features.

Repetitive patterns are common characteristics of aeolian features. Such replication leads to **dune fields** (extensive areas where dunes are of similar size and shape), and on the small scale it leads to fields of similarly shaped ripples on the slopes of dunes.

Aeolian Dust Deposits and Loess

A globally important effect of aeolian sediment transport is the deposition of silt-size, wind-blown sediment known as **loess.** Loess is the most geomorphically important aeolian sediment because of its tremendous geographic spread, its significance as parent material for agricultural soils, its erodibility, and the ability of continuous loess sections to preserve a long record of Quaternary climate and paleoenvironmental change.

The source of loess varies. Isotopic and geochemical tracing shows that some loess is derived from glacial outwash, other loess is derived from broad, poorly vegetated dryland basins, and some loess is derived from the erosion of soil developed on weak, fine-grained rock such as shale. Today, the fine-grained material that is deposited as loess originates primarily from the world's deserts. In glacial times, much loess was derived from glacial outwash plains—an inference supported by the thinning and fining of loess deposits away from these sources (Figure 10.8).

Distinct beds of loess cover an estimated 5–10 percent of Earth's surface and up to 30 percent of the United States [**Photograph 10.22**]. Blankets of thick loess cover much of midwestern North America, the Pampas of Argentina, and central Europe. In Alaska, extensive deposits of loess preserve important archaeological and fossil sites. Parts of China retain an astonishing thickness of loess (locally more than 100 m) in the huge Chinese loess plateau [**Photograph 10.23**] that records more-or-less continuous deposition (at varying rates) for more than 3 million years. The Chinese loess preserves one of highest-resolution, long-term terrestrial records of changing climate and landscape response on the planet.

Loess deposition tends to be ongoing, forming **cumulic** (or accumulating) soils (see Chapter 3); however, the rate of loess deposition changes over time as conditions in both the source and deposition areas change. In many places, loess deposition rates increased during glacial times when the climate was drier, colder, and windier. During interglacial times, loess deposition slowed, allowing soil development to proceed at a rate sufficient to create distinct soil horizons

PHOTOGRAPH 10.21 Sand Dunes and Loess. Sand blowing across ripples in the dune fields of the Gobi Desert. Saltating sand grains collide and fracture if wind speeds are high enough, forming silt that is deposited as desert loess.

PHOTOGRAPH 10.22 Fertile Loess Deposits. Thick, fine-grained, tan loess deposits in the Palouse region of southeastern Washington State are fertile areas in which to grow wheat. Here, the loess is exposed in a road cut several meters high, below the wheat. The rounded hills are typical of areas with thick loess, which blankets and buries pre-existing topography.

TAO Images/SuperStock

PHOTOGRAPH 10.23 China Loess Deposits. In the loess plateau of northern China, the hillslopes are extensively terraced to reduce erosion of the loess from runoff.

[Photograph 10.24]. If distinct layers of loess are seen in soil profiles, accumulation rates must have been high, otherwise loess deposited at low rates would have been stirred into and mixed with the soil by biological and physical turbation processes.

Even in areas where distinct blankets of loess cannot be mapped, the addition of wind-deposited dust may also significantly alter soil properties (see Digging Deeper). Some surfaces, such as desert pavements, are excellent natural dust traps. Incorporation of dust infiltrating down into a permeable soil may eventually clog pore spaces and decrease permeability enough to alter the intensity and pace of chemical weathering as well as the stability of surficial materials. If water cannot infiltrate because subsurface pores are clogged by fine sediment, it will run off, creating rills and eventually gullies. Near the ocean and on dry inland salt lakes or playas, wind can erode and carry sediment rich in salts (Photograph 10.7). When these salts are deposited on the surface of rocks they can increase rates of physical weathering as they dissolve and recrystallize (see Chapter 3).

Fine-grained soils (the parent material of which is often loess) are particularly vulnerable to both wind and water erosion if stripped of their vegetation cover. For example, during the Dust Bowl era of the 1930s, wind eroded loess-derived soils from the North American Great Plains and sent clouds of soil, in the form of dust, eastward. These soils had been stable since the last glaciation, held tightly under the thick mollisol A horizons and the root mats of prairie grasses until sod-busting plows removed the vegetative cover. When nearly a decade of drought hit the Great Plains in the 1930s, there was nothing to hold the dry, fine-grained soil in place, and it blew away **[Photograph 10.25]**.

Recent research has shown that many soils contain large amounts of dust delivered from far-off sources by wind. For example, the presence of elements such as chromium, thorium, and zirconium in soils on the calcium carbonate-dominated Caribbean island of Barbados indicates significant aeolian contributions including volcanic ash from the island of St. Vincent, dust eroded from Africa, and Mississippi River Valley loess. U.S. Geological Survey data indicate that African dust is an important component of soils developed on many western Atlantic Ocean islands and that aeolian dust, both because of the nutrients associated with it and because it contains clay with high cation-exchange capacity that increases nutrient retention, is important for sustaining regional vegetation. Similarly, soils in the Hawaiian Islands contain significant amounts of continentally derived dust from Asia, identified by its quartz content. We know this dust is derived from afar because the basaltic rocks of Hawaii contain no quartz.

N. Rutter

PHOTOGRAPH 10.24 Paleosols and Loess. Red paleosols alternate with loess in a section exposed on the Chinese loess plateau. The exposure is 150 m high and includes loess deposited over the past 2 million years.

A. Rothstein/Library of Congress

PHOTOGRAPH 10.25 Dust Bowl Soil Erosion. Wind stripped soil from fields during the Dust Bowl years of the 1930s, burying farms in sand and dust, as in this photo from Dodge City, Kansas, 1935.

The global flux of dust changes significantly over several different timescales. Climate controls dust flux on geologic timescales; most important are linked changes in water balance and global hydrology **[Figure 10.12]**. Over glacial-interglacial cycles, dustiness ebbs and flows with the coming and going of ice sheets. Glacial periods tended to be dustier because extensive outwash plains provided a source for dust, the climate was drier, vegetation near the ice was reduced, and the atmosphere was likely windier. On millennial timescales, warmer and drier climates, such as those prevalent in some parts of the world during the middle Holocene, likely led to increased dustiness. In the last millennia, humans have greatly increased the global dust flux over its natural

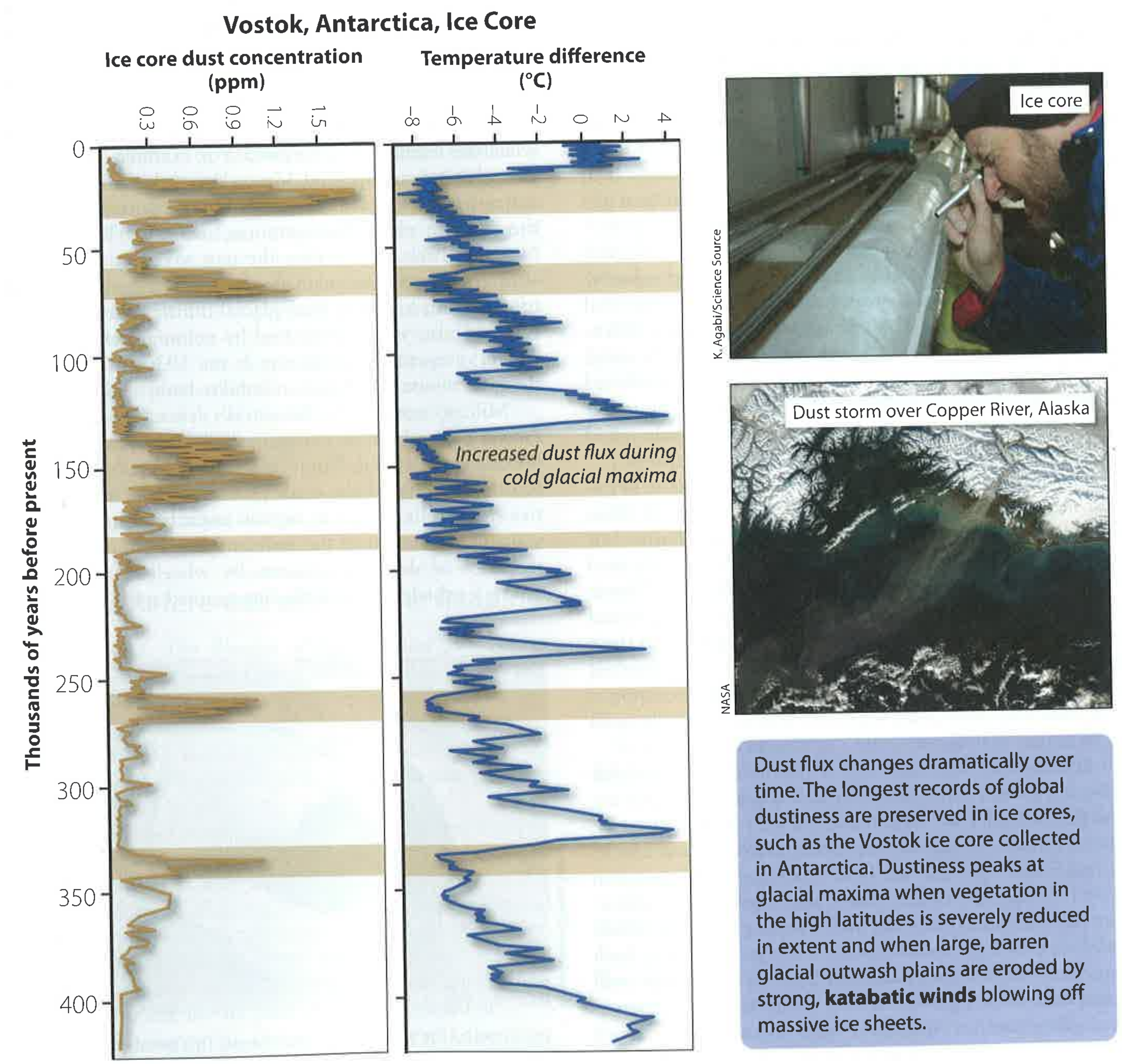


FIGURE 10.12 Dust Flux Changes Over Time. The ice core from Vostok in Antarctica records changes in dust flux over the past 400,000 years. More dust is delivered to the ice during glacial periods when temperatures are cold, vegetation is reduced, and the climate is, in general, drier.

background levels, primarily by removing vegetation, plowing fields, grazing animals, and using unpaved roads for vehicles.

Applications

Understanding wind's direct and indirect effects on Earth surface processes and the distribution of earth materials is critical for a variety of land management applications. Wind's direct geomorphic effects are most easily noticed where water is scarce and fluvial and hillslope processes are slow or limited in extent. The indirect effects of aeolian processes are far more widespread but less apparent. They include biological and physical disturbances caused by wind and the pervasive aeolian addition of moisture-holding, fertile, fine-grained parent material to soils, including rich soils used for agriculture that are critical for human survival in much of the world. Wind transport can move fine-grained material long distances in suspension before depositing it in diverse environments including silt-rich soil A horizons that support desert pavements (see Chapter 3; see also Digging Deeper) and the sediments that coat the deep abyssal plains of the world's oceans (see Chapter 8).

Wind both erodes and deposits materials at Earth's surface. Wind-induced erosion can rapidly strip valuable topsoil from agricultural areas, lofting fine-grained material in suspension as great dust storms and depositing it downwind tens, hundreds, even thousands of kilometers away. The massive 2009 dust storm in Australia that blanketed Sydney in an orange haze and the 2012 storm that shut down Arizona's interstate highways indicate the widespread and continuing nature of aeolian sediment transport.

Dry, terminal lake basins are important sources of silica- and metal-bearing dusts at a global scale. Some of these dusts can contain toxic or hazardous air pollutants. For example, desiccation of several large, internally drained lakes including Owens Lake in southern California (Photograph 10.7) and the Aral Sea in central Asia have allowed strong winds to erode a mix of salts that precipitated as these lakes dried. People and livestock living downwind are exposed to toxic dust that includes arsenic, chromium, copper, molybdenum, nickel, lead, silica, and uranium at levels equal to or higher than those found in industrialized areas.

Loess, wind-deposited silt, is the parent material for some of Earth's most fertile soils. Because loess soils are fine-grained, they are susceptible not only to wind erosion but to erosion by flowing water. Rates of soil loss can be astounding. In parts of the Palouse of eastern Washington State (Photograph 10.22), where wheat yields are extraordinarily high on native soils, more than a meter of this rich, wind-derived soil has been lost in the past century. Such rates of erosion are unsustainable and if they continue, will result in severely diminished crop yields. Various conservation techniques have been developed and applied to reduce wind erosion of agricultural soils including planting wind breaks and orienting fields perpendicular to predominant winds. Conversely, encroachment of wind-transported sediment can be a problem in coastal zones and around oases where dunes and sand are migrating **[Photograph 10.26]**.

Human actions can destabilize regions underlain by fine-grained, wind-deposited sediment. The removal of trees and shrubs for agriculture in marginal, semi-arid landscapes, such as portions of west Africa, triggers desertification (drying of the land surface) by changing the soil's water-holding capacity and the regional water balance. Both the change in water balance and the removal of effective cohesion provided by the plants can expose soils to greatly accelerated wind erosion.

Deposition of wind-transported sediment can have unexpected consequences. For example, human disturbance of stable soil profiles in the southwestern United States has increased dust loads to Rocky Mountain snowpacks. The darkening of the snow has reduced the reflection of sunlight, increased spring melting, and reduced summer streamflow, leading to water-management concerns.

There are numerous examples of dunes being reactivated when the vegetation is removed. For example, once-stable coastal dunes on Cape Cod, Massachusetts, became extremely active when European settlers removed the trees that held the sand in place. Revegetation, instituted by the U.S. National Park Service over the past several decades, has slowed rates of dune migration and kept most of the sand off the main highway. Post-glacial dunes in interior New England also were reactivated by colonial deforestation. There, revegetation programs in the 1930s planted hundreds of thousands of trees to stabilize bare, sandy slopes.

Military activities in the world's deserts are inexorably linked to and often constrained by aeolian processes (Photograph 10.6a). Some dust storms are natural, the result of strong winds, often generated by severe convective storm cells. However, human impacts on fragile desert soils often exacerbate the problem. For example, the disturbance of desert pavements by wheeled and tracked military vehicles exposes the fine-grained soil below. Once a pavement has been disturbed, it can take decades to reestablish; meanwhile, rare but intense rainfalls and strong desert winds scour the silt and lift billowing clouds of dust into the air. The resulting high concentrations of airborne particles clog air filters and damage engines and military equipment.

Stabilized or buried dunes can serve a variety of purposes that benefit society. For example, aquifers such as the Ogallala, which supports much of the irrigated agriculture of the western United States, are hosted in part within permeable, ancient dune sands. Areas of western North America covered by sand sheets with high infiltration rates are less likely to be affected by erosive processes that lead to deep arroyo cutting and massive sediment export because the permeable nature of the sand retards sapping and retrogressive headcut advance. On the Colorado Plateau, a surprisingly large area of the landscape that was once dominated by fluvial erosion has become progressively buried by aeolian materials, perhaps the result of Pleistocene aridity. This influx of aeolian sediment had resulted in profound changes in subsequent landscape evolution mostly related to differences in infiltration capacity and cohesion.

Wind-deposited sediments are an important archive of Earth's history. For example, the orientation of dunes and wind-sculpted features such as yardangs allows us to decipher wind patterns of the past, and older, continuous loess deposits preserve in their geochemistry and physical sedimentology a record of a changing Pleistocene climate. Deciphering geologic records of aeolian activity helps us to understand Earth's response to prior warming, cooling, wetting, and drying. Understanding the response of Earth's aeolian system to past changes in climate is of particular importance as we try to predict our planet's reaction to human-induced climate change.

Georg Gerster/Science Source

PHOTOGRAPH 10.26 Wind and Oases. This aerial view of Souf Oasis in Algeria shows the series of wind fences placed to protect the palm trees from being overrun by sand moved by wind in the Sahara Desert.

Selected References and Further Reading

Bagnold, R. A. *The Physics of Blown Sand and Desert Dunes*. Chapman and Hall: London, 1941.

Bauer, B. O. Contemporary research in aeolian geomorphology. *Geomorphology* 105 (2009): 1–5.

Bristow, C. S., G. A. T. Duller, and N. Lancaster. Age and dynamics of linear dunes in the Namib Desert. *Geology* 35 (2007): 555–558.

Ewing, R. C., G. Kocurek, and L. W. Lake. Pattern analysis of dune-field parameters. *Earth Surface Processes and Landforms* 31 (2006): 1176–1191.

Gillies, J. A., W. G. Nickling, and M. Tilson. Ventifacts and wind-abraded rock features in the Taylor Valley, Antarctica. *Geomorphology* 107 (2009): 149–160.

Goudie, A. S., and N. J. Middleton. *Desert Dust in the Global System*. Berlin, New York: Springer, 2006.

Hack, J. T. Dunes of the western Navajo Country. *Geographical Review 31* (1941): 240–263.

Hugget, R. J. *Fundamentals of Geomorphology*. Abingdon, Canada: Routledge, 2003.

Kocurek, G., and N. Lancaster. Aeolian system sediment state: Theory and Mojave Desert Kelso dune field example. *Sedimentology* 4 (1999): 505–515.

Laity, J. E. "Landforms, landscapes, and processes of aeolian erosion." In A. D. Abrahams and A. J. Parsons, eds., *Geomorphology of Desert Environments*, 2nd ed. New York: Springer, 2009.

Lancaster, N. *Geomorphology of Desert Dunes*. London: Routledge, 1995.

Livingstone, I., and J. E. Bullard. "Dust." In A. D. Abrahams and A. J. Parsons, eds., *Geomorphology of Desert Environments*, 2nd ed. New York: Springer, 2009.

Livingstone, I., and A. Warren. *Aeolian Geomorphology: An Introduction*. New York: Longman, 1996.

Livingstone, I., G. F. S. Wiggs, and C. M.Weaver. Geomorphology of desert sand dunes: A review of recent progress. *Earth Science Reviews* 80 (2007): 239–257.

Macpherson, T., W. G. Nickling, J. A. Gillies, and V. Etyemezian. Dust emissions from undisturbed and disturbed supply-limited desert surfaces. *Journal of Geophysical Research* 113 (2008): F02S04. doi: 10.1029/ 2007JF000800.

McKee, E. D., ed. *A Study of Global Sand Seas*, Professional Paper 1052. United States Geological Survey, 1052.

Montgomery, D. R., J. L. Bandfield, and S. K. Becker. Periodic bedrock ridges on Mars. *Journal of Geophysical Research* 117 (2012): E03005. doi: 10.1029/2011JE003970.

Muhs, D. R. The geologic records of dust in the Quaternary. *Aeolian Research* 9 (2013): 3–48.

Muhs, D. R., J. R. Budahn, J. M. Prospero, and S. N. Carey. Geochemical evidence for African dust inputs to soils of western Atlantic islands: Barbados, the Bahamas, and Florida. *Journal of Geophysical Research* 112 (2007): F02009. doi: 10.1029/2005JF000445.

Parsons, A. J., and A. D. Abrahams, eds. *Geomorphology of Desert Environments*. New York: Springer, 2009.

Summerfield, M. A. *Global Geomorphology*. New York: Prentice Hall, 1991.

Sun, J., and D. R. Muhs. "Mid latitude dune fields." In S. A. Elias, ed., *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, 2007.

Thomas, D. S. G. *Arid Zone Geomorphology*. Chichester: Wiley-Blackwell, 2011.

Warren, A., A. Chappell, M. Todd, et al. Dust-raising in the dustiest place on Earth. *Geomorphology* 92 (2007): 25–37.

Wells, S. G., L. D. McFadden, and J. D. Schultz. Eolian landscape evolution and soil formation in the Chaco dune field, southern Colorado Plateau, New Mexico. *Geomorphology* 3: 517–546.

Wolfe, S. A. "High latitude dune fields." In S. A. Elias, ed., *Encyclopedia of Quaternary Science*. Amsterdam: Elsevier, 2007.

Yair, A., and Y. Enzel. "The relationship between annual rainfall and sediment yield in arid and semi-arid areas: The case of the northern Negev." In F. Ahnert, ed., *Geomorphological Models—Theoretical and Empirical Aspects*, Catena Supplement No. 10, pp. 121–135. Cremlingen-Destedt, Germany: Catena Verlag, 1987.

DIGGING DEEPER Desert Pavements—The Wind Connection

Stone pavements, flat, closely packed collections of clasts, cover many desert surfaces. These pavements are present on residual weathering mantles, overlie lava flows, and form on alluvial deposits. In many areas, the exposed surfaces of pavement stones are covered by a thick coating of dark, shiny rock varnish, a manganese-iron-rich surface coating found on stable rock surfaces in arid regions.

Pavements are known by different names in different regions of the world. They are gibber plains in Australia and regs in North Africa. In central Asia, gobi is the term used to describe pavements. In the southwestern United States, they are known as desert pavements. Some pavements are exceptionally old, such as those in Israel for which ^{10}Be measurements suggest ages of several million years, making the plains on which the pavements reside some of the oldest large-scale landforms found to date (Matmon et al., 2009).

Most pavements are only a clast or two thick and are underlain by vesicular, fine-grained A horizons centimeters to a few tens of centimeters thick with columnar structure indicative of shrink-swell behavior driven by clays. The A horizon is composed predominantly of quartz-rich, sandy silt and is punctuated by vesicles, small air-filled pockets. It is known as an Av horizon with the "v" indicating that it is vesicular. The A-horizon vesicles result from trapped air bubbles locked in place when the soil dries after rainfalls. Below the Av horizon is a massive, fine-grained B horizon with few clasts [**Figure DD10.1**].

As a landform, pavements were long enigmatic. Pavement formation has been attributed to a variety of processes including selective fluvial erosion washing away fine material, deflation by wind leaving a lag of coarse clasts, and upward migration of stones carried by a clay-rich argillic B horizon (born-in-place model). Wind figures prominently in the latter two of these three explanations.

Sheet flooding (overland flow) has been suggested as a mechanism by which to move clasts and to remove the silt and thus the matrix between the clasts. There is evidence that sheet flooding can effectively move clasts and even arrange them in a crude mosaic where they lay next to each other on an impermeable substrate, in one case, a recent basalt flow (Williams and Zimbelman, 1994). However, the sheet-flood model of pavement formation does not explain well the presence of the stone-free A horizon underlying the pavement. Similarly, the deflation model, where wind removes the fines and leaves the clasts, cannot explain the underlying Av horizon [**Figure DD10.2**].

The born-in-place or accretionary model (McFadden et al., 1987) has evolved from observations over the past several decades (starting with Cooke, 1970), is gaining wider acceptance, and has been tested using measurements of a cosmogenic stable nuclide, ^{3}He (Wells et al., 1995).

The accretionary model posits that clasts originally at the surface stay at the surface as fine-grained, wind-transported

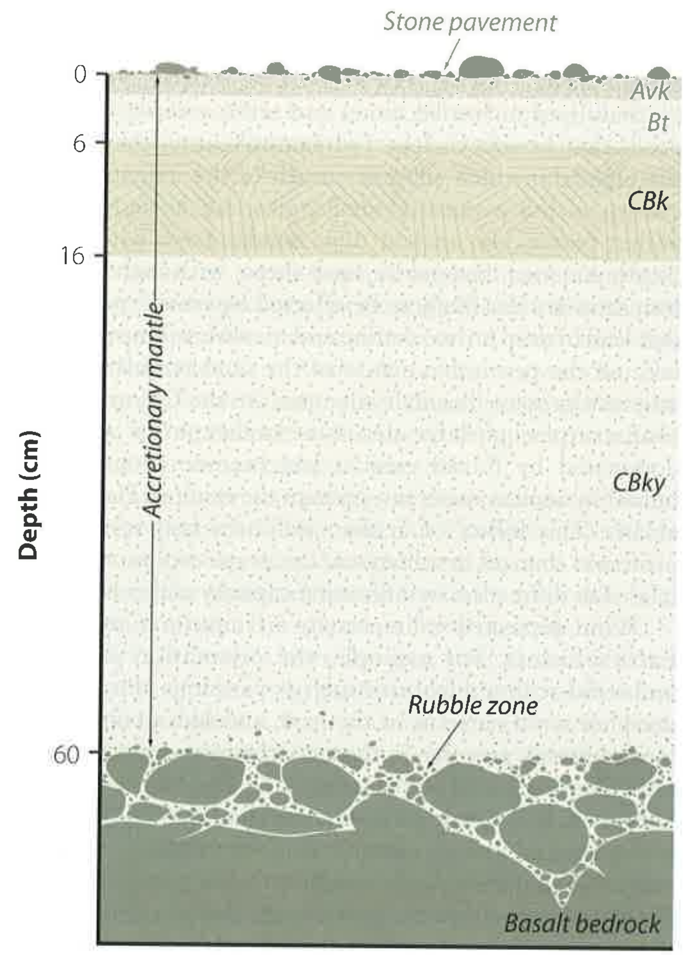


FIGURE DD10.1 Cross section of typical desert pavement shows the one- to two-clast-thick layer at the surface underlain by the thin Av horizon with some calcium carbonate (the letter k designation). Below the Avk horizon, is a Bt horizon (where clay has accumulated, as indicated by the letter t). It is underlain by a two-part, carbonate-rich C horizon where the letter k indicates the presence of carbonate and the letter y indicates the presence of gypsum. The letter B following the C indicates that C-horizon properties dominate but that some B-horizon properties are present. The basalt bedrock from which Wells et al. (1995) believed the surface clasts originated is at the base of the cross section. [From Wells et al. (1995).]

material accumulates beneath them. The process is thought to work like this. The initially rough, rocky surface (such as a fresh deposit on a desert fan or a new basalt flow) functions as a dust trap, slowing the wind and encouraging deposition of aeolian silt and clay. Each year, small amounts of aeolian material are added to the surface. The silt is washed between the clasts and into the developing soil, accumulating in thickness over time.

Clay, brought in on the wind with the dust, is critical to cumulic soil development (the thickening of soil over time). Because clay shrinks and swells as it wets and dries, its

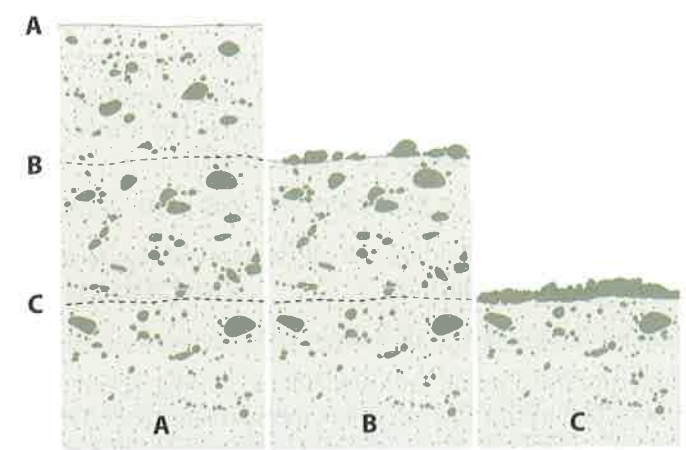


FIGURE DD10.2 Deflation, the removal of fine material from geomorphic surfaces by wind, has long been proposed as a means by which pavements could form. In this view, the pavement is the lag deposit of gravel left behind because wind speeds, although sufficient to remove silt and sand, were insufficient to remove gravel. Over time (indicated by the letters A, B, and C), the amount of gravel on the surface increases as fines from the underlying deposit are removed. The dashed line shows the depth to which the surface will erode in later time steps. [From Cooke (1970).]

behavior enables aeolian material to get below the pavement. Shrinking produces conduits (fractures) that enable transport of soil water and associated suspended clay, solutes, and fine silt below the soil surface, making possible continued deposition and pedogenic alteration of the fine-grained material. Over time, soil development in the fine-grained dust produces peds defined by columnar structure. After thousands of years, the source of the clasts, be it a lava flow or an alluvial deposit, is buried by accumulated aeolian material while the loose clasts continue to "float" at the surface. If this model is correct, pavements are born at the surface and rise over time as dust accumulates below them.

The accretionary model was verified for pavements in the Mojave Desert using the cosmogenic nuclide, ^{3}He. Wells et al. (1995) collected clasts from several pavements developed on basalt flows of varying age in the Cima volcanic field, an active area of basaltic volcanism in southern California. The concentration of ^{3}He in pavement clasts closely matched that in samples collected from basalt outcrops near the pavements [**Figure DD10.3**]. Such a match could only happen if both the pavement clasts and the basalt-flow surfaces had the same exposure history (exposure age), revealing that the pavement clasts, just like the sampled basalt flow surfaces, have been at the surface since they were incorporated into the pavement.

The accretionary pavement model is attractive because it can explain all of the observed features of desert pavements: the paucity of clasts in the B horizon, similar

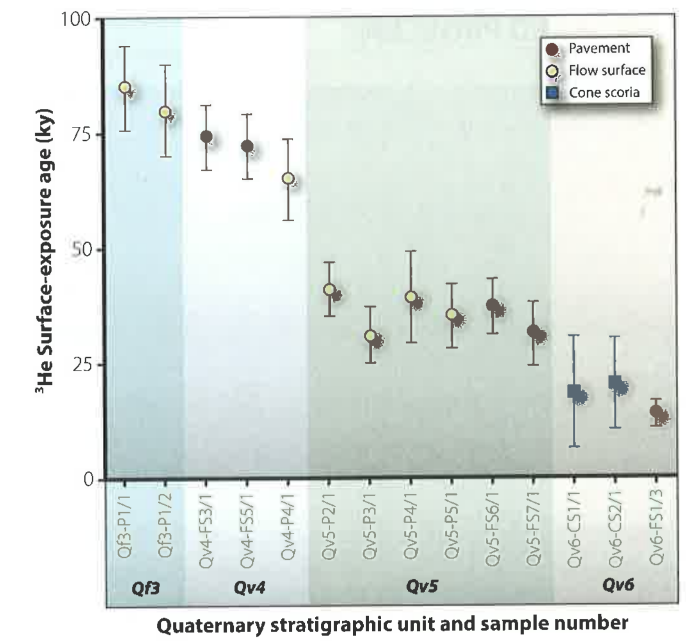


FIGURE DD10.3 Cosmogenic ^{3}He exposure ages measured in desert pavement clasts, basalt flow surfaces, and scoria from basalt flows of four different ages in Cima volcanic field, Mojave Desert. For any one unit, the ages of the clasts in the pavement are indistinguishable for the ages of the flows from which they were derived. This study shows that clasts in the pavements had the same exposure history as the flows, which would be possible only if the clasts had remained at the surface since they were erupted. [From Wells et al. (1995).]

cosmogenic ages for clasts and associated outcrops, and the thick Av horizon.

Cooke, R. U. Stone pavements in deserts. *Annals of the Association of American Geographers* 60 (1970): 560–577.

Matmon, A., O. Simhai, R. Amit, et al. Desert pavement–coated surfaces in extreme deserts present the longest-lived landforms on Earth. *Geological Society of America Bulletin* 121 (2009): 688–697.

McFadden, L. D., S. G. Wells, and M. J. Jercinovich. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. *Geology* 15 (1987): 504–508.

Wells, S. G., L. D. McFadden, J. Poths, and C. T. Olinger. Cosmogenic ^{3}He surface-exposure dating of stone pavements: Implications for landscape evolution in deserts. *Geology* 23 (1995): 613–616.

Williams, S. H., and J. R. Zimbelman. Desert pavement evolution: An example of the role of sheetflood. *Journal of Geology* 102 (1994): 243–248.

DIGGING DEEPER Desert Pavements—The Wind Connection *(continued)*

WORKED PROBLEM

Question: Stokes' Law (eq. 10.1) describes the settling of solid material though a viscous fluid assuming laminar-flow conditions:

$$S_s = 2r^2(\rho_p - \rho_f)g/9\mu_f$$

First, calculate the settling speed (S_s) of coarse silt (63 μm diameter, r = 0.0000315 m) and sand (500 μm diameter, r = 0.000250 m). Assume a rock density (ρ_p) of 2700 kg/m^3 and a density of air (ρ_f) of 1.225 kg/m^3. The dynamic viscosity of air (μ_f) at 20 °C is 1.983×10^{-5} kg/(m × s).

Then, consider how long the sand and silt grain would each take to settle from the top of a 1-km-high dust cloud that resulted from a major sand storm.

Answer: Once you fill in the variables in eq. 10.1, the only change you need to make is r, the radius of the particle, which for consistency with other variables in eq. 10.1, needs to be expressed in meters. The answer is in meters per second (do the unit analysis):

$$S_s = 2r^2(2700 - 1.225)9.8/(9 \times 1.983 \times 10^{-5})\text{ m/s}$$

Multiplying and dividing out all the nonvariable terms, this expression reduces to

$$S_s = r^2 \times 2.96 \times 10^8 \text{ m/s}$$

Incorporating grain radius yields a settling speed of about 18.5 m/s for 500 μm grains, medium sand. For 63 μm grains, coarse silt, the settling speed is about 0.29 m/s. Hence, it would take sand grains only (1000 m/18.5 m/s) or 54s to settle from a 1 km elevation, whereas it would take silt grains (1000 m/0.29 m/s) more than 3400s or nearly an hour to settle the same distance.

KNOWLEDGE ASSESSMENT Chapter 10

1. Identify in what settings aeolian processes are the dominant geomorphic actors and explain why.
2. What is the predominant mineral in most aeolian sediment? Explain why.
3. Explain the influence of biologic activity on the intensity of aeolian geomorphic processes.
4. List some of the geomorphic effects of wind.
5. Compare and contrast the physical properties of water and air and explain what differences control the geomorphic effectiveness of these fluids.
6. Define turbulence and explain why it is important for understanding aeolian geomorphic processes.
7. What is a sediment state and why is it useful for understanding aeolian geomorphic systems?
8. Explain the difference between fluid and impact thresholds.
9. Explain how erosion processes differ for cohesive and noncohesive materials.
10. What is ventifaction and how and where does it occur?
11. What is aeolianite, how does it form, and where are you most likely to find it?
12. What was the effect of widespread Quaternary glaciation on rates of aeolian sediment deposition?
13. Make a diagram illustrating the differences in movement and typical particle size in transport for suspension, saltation, and creep.
14. What is Stokes' Law and why is it important for understanding aeolian geomorphic processes?
15. Which grain size is optimal for wind erosion? Explain why.
16. What is loess and what is the primary control on the grain size and thickness of loess deposits?
17. What is a yardang and where might you find one?
18. Draw a cross section of a desert pavement and explain the most commonly accepted mechanism of formation.
19. Explain how soil development strengthens soil over time, reducing the likelihood of wind erosion.
20. Compare the sizes and longevity of ergs, dunes, and ripples.
21. Give two examples of the aeolian geomorphic effects of high surface roughness.
22. Dunes can be separated into two distinct categories. List those categories and explain how they differ.
23. Explain how barchan, parabolic, and star dunes form and move, highlighting similarities and differences.
24. Give three examples of the importance of dust/loess in soil formation.
25. Explain how we know that the flux of dust carried by wind changed over time and why such changes have occurred.
26. Describe how aeolian sediment transport impacts humans and how humans impact aeolian sediment transport.
27. Explain how aeolian sediment transport contributes to the fertility of soils.