16 Eolian Systems

Geologists once thought that wind, like running water and glaciers, was an effective agent of erosion, but even in the deserts, few major topographic features are the result of wind abrasion. Wind can, however, pick up and transport large quantities of loose sand and dust. As a result, shifting sand dunes or thick sheets of wind-blown dust dominate the landscape in many areas—especially in low-latitude deserts, where precipitation is low and evaporation is high. The great "sand seas" that completely cover large areas of north Africa's Sahara Desert, Saudi Arabia, and central Australia are the most spectacular examples of wind activity on Earth, but sand dunes also occur in many coastal areas and in smaller "rain-shadow" deserts.

Even in the arid regions of the western United States, sand dunes are locally significant landforms. The Great Sand Dunes National Monument in Colorado, the Algodones dunes in southern California, and the Sand Hills of Nebraska are good examples of relatively small dune fields. The panorama above is from the rain-shadow desert in Death Valley, California. It vividly illustrates a landscape where wind is the dominant geologic process and huge sand dunes are the most striking feature.

Wind activity is also important in forming large deposits of wind-blown dust called loess that blanket millions of square kilometers in the mid-latitude continents, including portions of China, the central United States, and central Eurasia. Wind-blown dust covers about one-tenth of the land surface. This fact is important because soils from these deposits are some of Earth's richest farmland and are the foundation for a large percentage of the world's food supply. Wind-blown dust is also carried far out over the seas, where it settles to the floor of the ocean and forms sediment.

The eolian system, like other parts of the hydrologic system, takes its energy from the Sun and the uneven heating of the planet. Like water, it is a fluid that flows readily. Also like water, the wind picks up and transports huge volumes of sediment. Deposition and erosion are associated with distinctive landforms just as they are for streams, groundwater, and flowing ice. Thus, your challenge as you read this chapter is to clearly comprehend the similarities in the different components of the hydrologic system, but also to come to grips with the significant differences between the role of moving water versus moving air.

In this chapter, we consider eolian systems as geologic agents: how the wind erodes the surface, transports and deposits sediment, and forms unique features of the landscape.

MAJOR CONCEPTS

1. Wind is not an effective agent in eroding the landscape, but it can produce deflation basins and yardangs as well as small pits and grooves on rocks.
2. The major result of wind activity is the transportation of loose, unconsolidated fragments of sand and dust. Wind transports sand by saltation and surface creep. Dust is transported in suspension, and it can remain high in the atmosphere for long periods.
3. Sand dunes migrate as sand grains are blown up and over the windward side of the dune and accumulate on the lee slope. The internal structure of a dune consists of strata inclined in a downwind direction.
4. Various types of dunes form, depending on wind velocity, sand supply, and constancy of wind direction.
5. Wind-blown dust (loess) forms blanket deposits, which can mask the older landscape beneath them. The source of loess is desert dust or the fine rock debris deposited by glaciers. Some deep oceanic sediment is wind-blown dust from continents.
6. Desertification, the loss of farmable land on the margins of deserts, can be caused by human activity or by slight climatic fluctuations.

THE GLOBAL EOLIAN SYSTEM

The eolian system is a dynamic open system driven by heat from the Sun. The great deserts of the world, where the effects of the wind are most obvious, form in low-latitude regions in zones roughly 30° north and south of the equator. There wind lifts, transports, and eventually deposits loose sand and dust, but its ability to erode solid rock is limited.

Earth's eolian system is intimately tied to the hydrologic system and shares many common features with it. Like the hydrologic system, the eolian system is a manifestation of a moving fluid across the surface. In addition, the energy source for both is the same. The kinetic energy of the wind originates in the Sun and is radiated to Earth. The uneven heating of Earth's surface (see Figure 9.6) makes the atmosphere a vast convecting fluid that envelopes the entire planet. Prevailing wind patterns are determined by (1) variations of solar radiation with latitude, (2) the **Coriolis effect** (deflection due to Earth's rotation, see Figure 9.8), (3) the configuration of continents and oceans, and (4) the location of mountain ranges.

What controls the location of deserts?

The geologic effects of the wind are most obvious in deserts, where precipitation and runoff are low and vegetation is sparse. The locations of most deserts are controlled by the pattern of atmospheric convection (see Figure 9.8). The world's great deserts, such as the Sahara and the deserts of Asia, are mostly in low-latitude belts (Figure 16.1). As described earlier, humid equatorial air, heated by solar radiation, rises because it is buoyant. As the air rises to higher altitudes, it cools and releases its moisture, which falls as tropical rains in the equatorial regions. This air is much drier as it continues to convect poleward. Eventually, the dry air descends to the surface near 30° to 35° north and south of the equator. As the air descends, it warms, so it rarely produces any precipitation. Consequently, evaporation of surface moisture, rather than precipitation, occurs in the low latitudes where the convecting air descends. The trade winds move this air back to the equator, where it is again heated, humidified, and rises to start the cycle again. Dry descending air currents also create polar deserts, where precipitation is low, but so is the temperature.

Other deserts lie in **rain shadows,** behind high mountain ranges that intercept moisture-laden air currents. As the air is forced to rise over the mountain range, it cools and precipitates its moisture. On the other side of the range, the dry

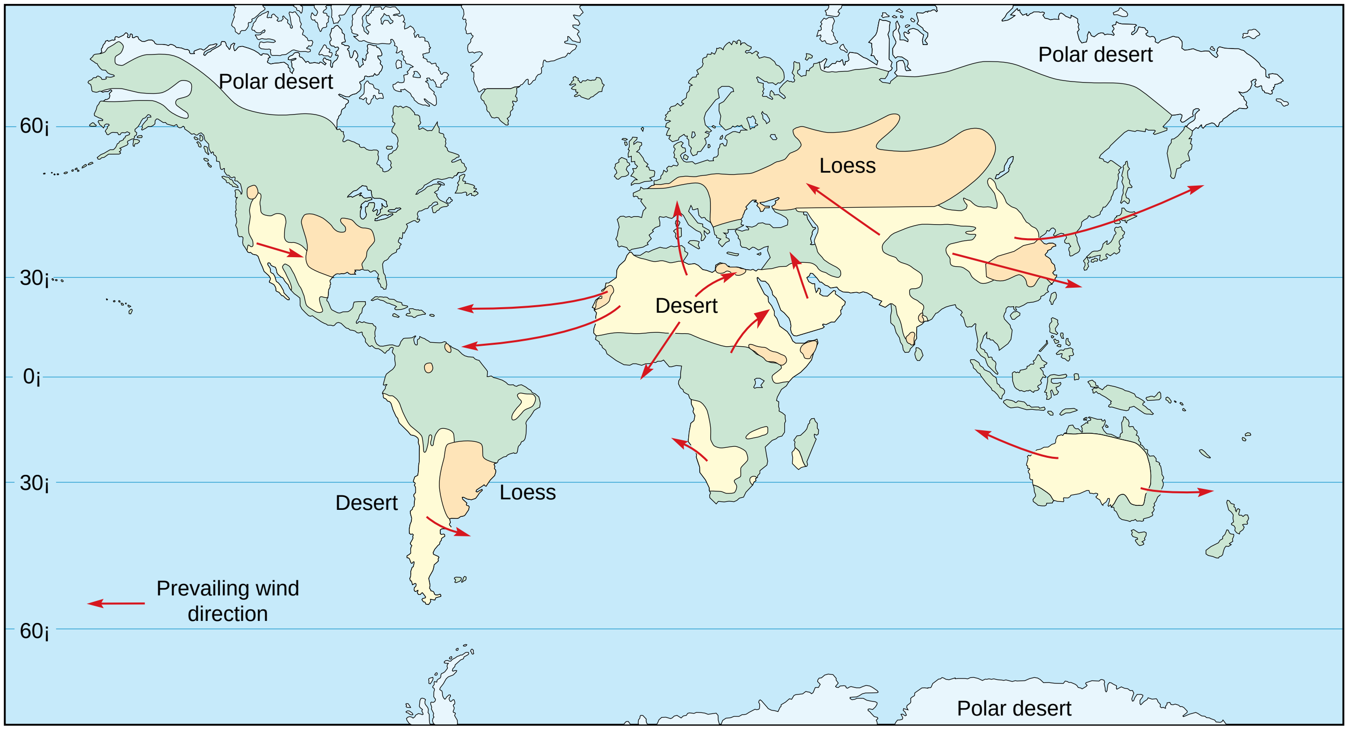


FIGURE 16.1 **The major deserts of the world,** the Sahara, the Arabian, the Kalahari, and the deserts of Australia, are near 30° north or south of the equator. These bands are under almost constant high atmospheric pressure where dry air subsides. Desert and near-desert areas cover nearly one-third of the land surface. Wind-blown dust (loess) accumulates downwind from major deserts or along former margins of Pleistocene glaciers. Prevailing winds (arrows) transport dust from the Sahara and Kalahari deserts to the Atlantic Ocean and from deserts of Australia to adjacent seas. Dry descending air currents also create polar deserts, where precipitation is low, but so is the temperature.

descending air is heated. The arid regions of Nevada and Utah lie in the rain shadow of the Sierra Nevada.

Wind action is most significant in desert areas, but it is not confined to them. Many coasts are modified by winds that pick up loose sand on the beach and transport it inland.

The eolian system is summarized in Figure 16.2. Weathering produces sediment particles in a range of sizes. Water transports some of this material downslope before it is picked up by the wind. The coarsest materials are left to form lag deposits; sand-size grains are transported and ultimately deposited to form sheets and dunes in the deserts; and the dust-sized materials are carried far away. Much of the dust is deposited in adjacent, more humid climates.

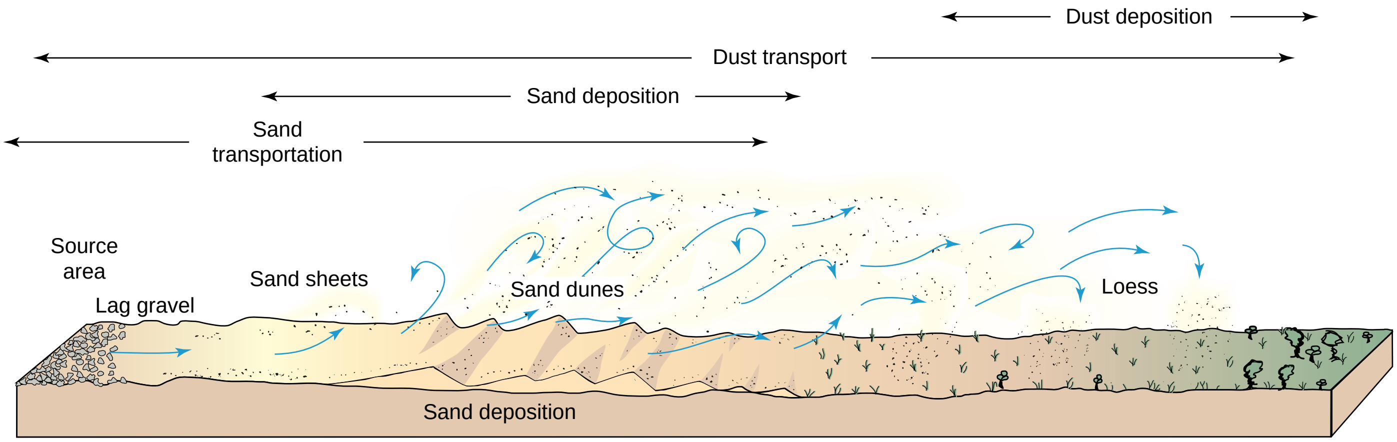


FIGURE 16.2 **The eolian system** is driven by energy from the Sun. Flowing air erodes, transports, and deposits fine sediment to form distinctive landforms and rock bodies. Sand sheets, sand dunes, and layers of loess are the major eolian deposits. Lags of coarse particles are left behind.

WIND EROSION

Wind erosion acts in two ways: (1) by deflation, the lifting and removal of loose sand and dust particles from Earth's surface, and (2) by abrasion, the sandblasting action of wind-blown sand.

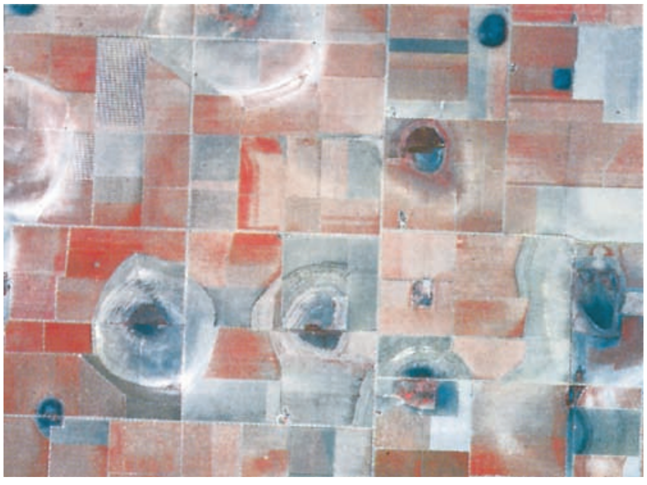
Why is the erosive power of wind less effective than that of running water?

Wind alone can do little to erode solid rock exposed at the surface, but it is capable of transporting loose unconsolidated material. For wind to be an effective agent of erosion, chemical and mechanical weathering must disintegrate solid rock into small loose fragments that can be picked up and transported. A dry climate is also necessary; in a humid climate vegetation usually covers the surface and holds loose particles together. In addition, wet material is usually cohesive because water tends to hold loose fragments together. On a small scale, wind can also abrade and polish solid rock surfaces.

Deflation

The most significant type of wind erosion is **deflation,** a process in which loose particles of sand and dust are lifted from the surface and blown away. The turbulence of the wind is able to lift these fine materials. Deflation commonly occurs in semiarid regions where the protective cover of grass and shrubs has been removed by the activity of humans and animals. The results are broad shallow depressions called **deflation basins.** Deflation basins also commonly develop where calcium carbonate cement, in sandstone formations, is dissolved by groundwater, leaving loose sand grains that are picked up and transported by the wind (Figure 16.3). Large deflation basins, covering areas of several hundred square kilometers, are associated with the great desert areas of the world, particularly in North Africa near the Nile Delta.

Perhaps the best example of wind erosion in the United States is in the Great Plains, especially the High Plains of Colorado, Kansas, and Texas. In this area, innumerable deflation basins—ranging from small dimples, 30 cm deep and 3 m in diameter, to larger basins, 15 to 20 m deep and more than a kilometer across—are scattered across the landscape (Figure 16.3). Many have permanent or intermittent lakes in them. Although some of these depressions may be the result of collapse and local subsidence, deflation has played a major role in their development.



(A) Deflation basins in the Great Plains of Texas are produced where solution activity in the layers of horizontal bedrock dissolves the cement that binds the sand grains. *(Courtesy of U.S. Geological Survey)*

(B) Small deflation basins in sandstone formations in the Colorado Plateau form in a similar manner.

FIGURE 16.3 **Deflation basins** are wind erosion features that range in size from small depressions to large basins several kilometers in diameter.

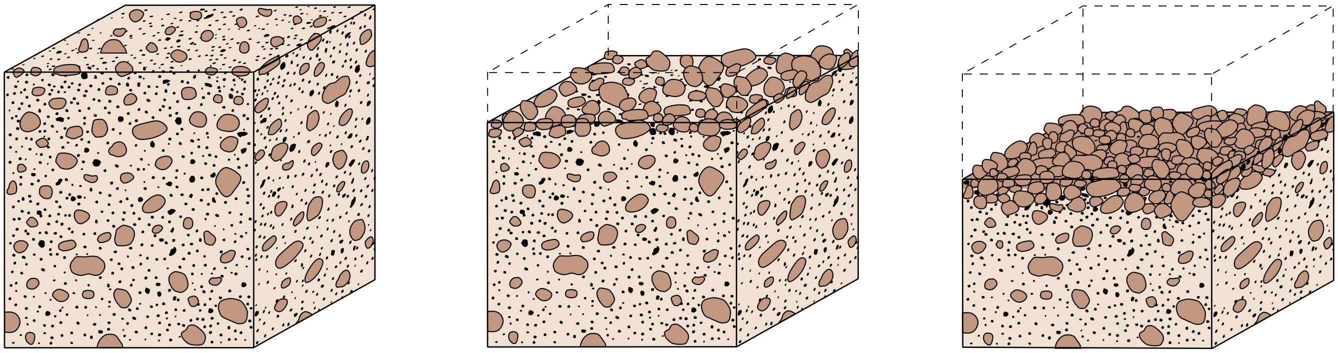


FIGURE 16.4 **Desert pavement** results as wind selectively removes sand and fine sediment, leaving the coarser gravels to form a lag deposit. The protective cover of lag gravel acts as an armor limiting future deflation.

During wet periods, water collecting in small depressions will dissolve the calcareous cement in the horizontal sandstone that covers the area. Thus, many of the individual grains in the sandstone formation are loose and free to move about. During dry periods, wind will pick up the loose grains and blow them away. This process creates a larger basin, which collects more water, which in turn dissolves more cement, to produce more loose grains. The process is therefore self-perpetuating. Many of these depressions are enlarged by the activity of animals. Animals were especially influential in the time when great herds of buffalo thronged to the temporary ponds for water. After wading and wallowing, the herds would carry away mud on their bodies and destroy the surrounding vegetation, producing conditions that favored further wind erosion. The depressions have thus been referred to as "buffalo wallows."

What are the major features produced by wind erosion?

In general, wind can move only sand and dust-sized particles, so deflation leaves concentrations of coarser material known as **lag deposits,** or **desert pavements** (Figure 16.4). These striking desert features of erosion (Figures 16.5 and 16.6) stand out in contrast to deposits in dune fields and playa lakes. Deflation occurs only where unconsolidated material is exposed at the surface. It does not occur where there are thick covers of vegetation or layers of gravel. The process is therefore limited to areas such as deserts, beaches, and barren fields.

Abrasion

Wind abrasion is essentially the same process as the artificial sandblasting used to clean building stone. Energy for abrasion comes from the kinetic energy of the wind. Wind-driven grains impact rock surfaces and small particles are knocked off the rock. Some effects of wind abrasion can be seen on the surface of the bedrock in most desert regions (Figure 16.7). In areas where soft, poorly consolidated rock is exposed, wind erosion can be both spectacular and distinctive. Some pebbles, known as **ventifacts** (literally meaning "wind-made"), are shaped and polished by the wind (Figures 16.7 and 16.8). Such pebbles are commonly distinguished by two or more flat faces that meet at sharp ridges and are generally well polished. Some faceted ventifacts are up to 3 m long. Other ventifacts have a variety of shapes. Some have surface irregularities, pits, and grooves, or U-shaped depressions with roughly parallel sides aligned with the wind direction (Figure 16.7).

Larger landforms produced by wind abrasion are less common, but in some desert regions, distinctive linear ridges, called **yardangs,** are produced by wind erosion. These features were first discovered in China's Taklimakan Desert. The name is derived from the Turkistani word *yar,* meaning "ridge" or "bank." Typical yardangs have the form of an inverted boat hull (Figure 16.9) and commonly occur in clusters, oriented parallel to the prevailing wind that formed them. Theoretically, they can be formed in any rock type, but they are best developed in soft, unconsolidated, fine-grained sediment or volcanic ash that is

FIGURE 16.5 **Lag gravels** consist of angular clasts that range from fragments 30 cm or so across to small pebbles. Once the clasts become concentrated like this, they protect the surface from further erosion.

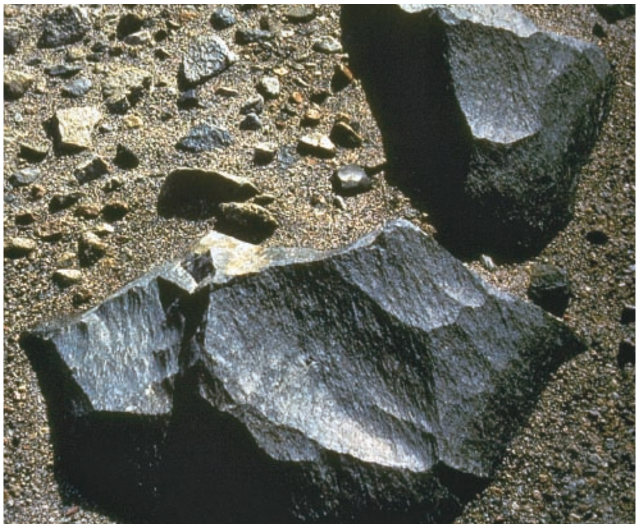
FIGURE 16.6 **Lag gravel** and desert pavement, not sand dunes, are major parts of the landscape in many desert regions like the Sahara Desert in Morocco. Desert pavement forms where small particles are swept away by the wind.

easily sculpted but is cohesive enough to retain steep slopes. Yardangs evolve into streamlined shapes that offer minimum resistance to the moving air. In a way, they are analogs to drumlins, which are shaped by moving ice. This shape may involve the combination of erosion with deposition to sculpt the flanks or the end of the yardang.

Yardangs are generally restricted to the most arid parts of deserts, which are relatively sand-poor and are areas where vegetation and soil are minimal. There is some indication that the Sphinx in Egypt was constructed out of a yardang.

Some of the most spectacular wind erosional features on Earth are the great yardangs of the Tibesti area of Chad in northern Africa (Figure 16.10). There, ridges almost 150 m high and several kilometers long are carved by the wind out of nonresistant sediments. The ridges are separated by troughs 100 m or more wide. There are no stream erosion channels between the yardangs, and no evidence of water erosion can be seen on the floor of the yardang field.

(A) Grooves eroded on bedrock near Palm Springs, California.



(B) Ventifact shaped by wind abrasion into flat surfaces. *(Courtesy of U.S. Geological Survey)*

FIGURE 16.7 **Wind abrasion** is a process very much like sandblasting. Grooves and polished surfaces are apparent on cobbles and on bedrock in most of the world's deserts.

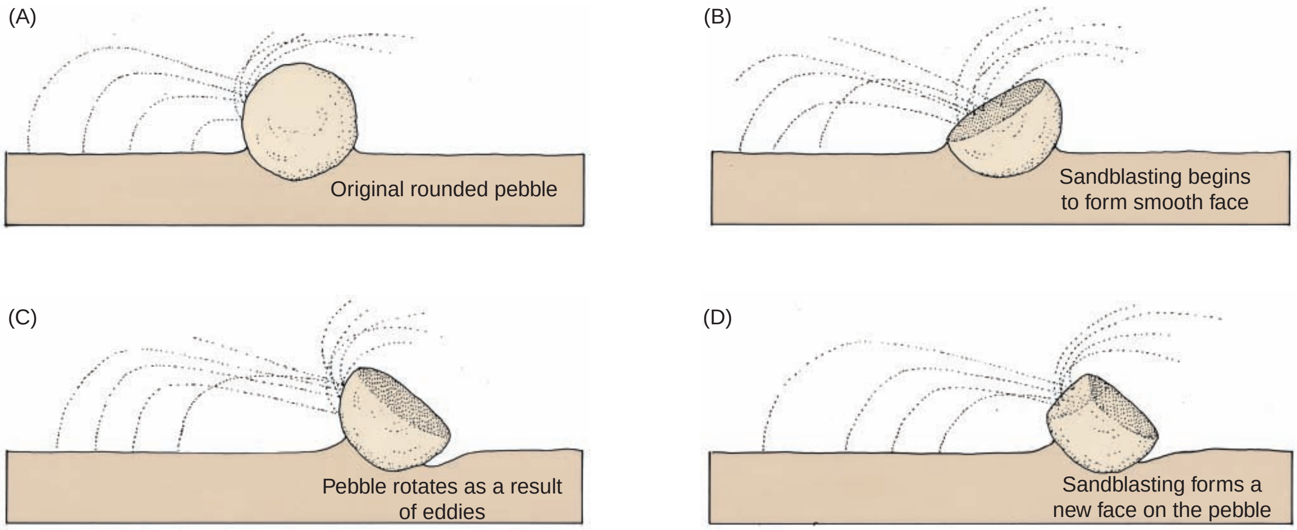


FIGURE 16.8 **Ventifacts** are pebbles shaped and polished by wind action. They commonly have two or more well-polished sides formed as the sandblasting action of wind reshapes one side and then another. In (B), a facet (smooth face) is formed by sandblasting on the side facing the prevailing wind. Removal of the sand by deflation causes the pebble to rotate so that another faceted and polished surface is produced on another side of the pebble (D).

TRANSPORTATION OF SEDIMENT BY WIND

Wind transports sand by saltation and surface creep. Silt and dust-sized particles are carried in suspension.

Movement of Sand

Although both wind and water transport sediment, the mechanics of motion involved are somewhat different because the viscosity of water is much greater than that of air. A sediment grain can be picked up by the wind when the forces acting to move the grain overcome the forces resisting movement. The main forces resisting motion are the weight of the grain and its cohesion to other grains. Wind blowing over the surface creates aerodynamic lift and drag on a grain. **Lift** is caused by the air flowing over the grain, creating a zone of low air pressure over the grain. (This is the same lift generated above the top of an airplane's wing.) The low pressure causes the grain to be "sucked" into the air flow. **Drag** is caused by the impact of air molecules on the grain's surface. High-speed photography shows that a particle begins to shake and then lifts off, spinning into the air. A critical wind velocity must be reached before a grain of a certain size will begin to move. For sand-sized grains with diameters of about 0.1 mm, this critical wind velocity

FIGURE 16.9 **Yardangs** are elongate ridges formed by wind erosion of relatively soft material. Note the streamlined shape. *(Photograph by Alan L. Mayo)*

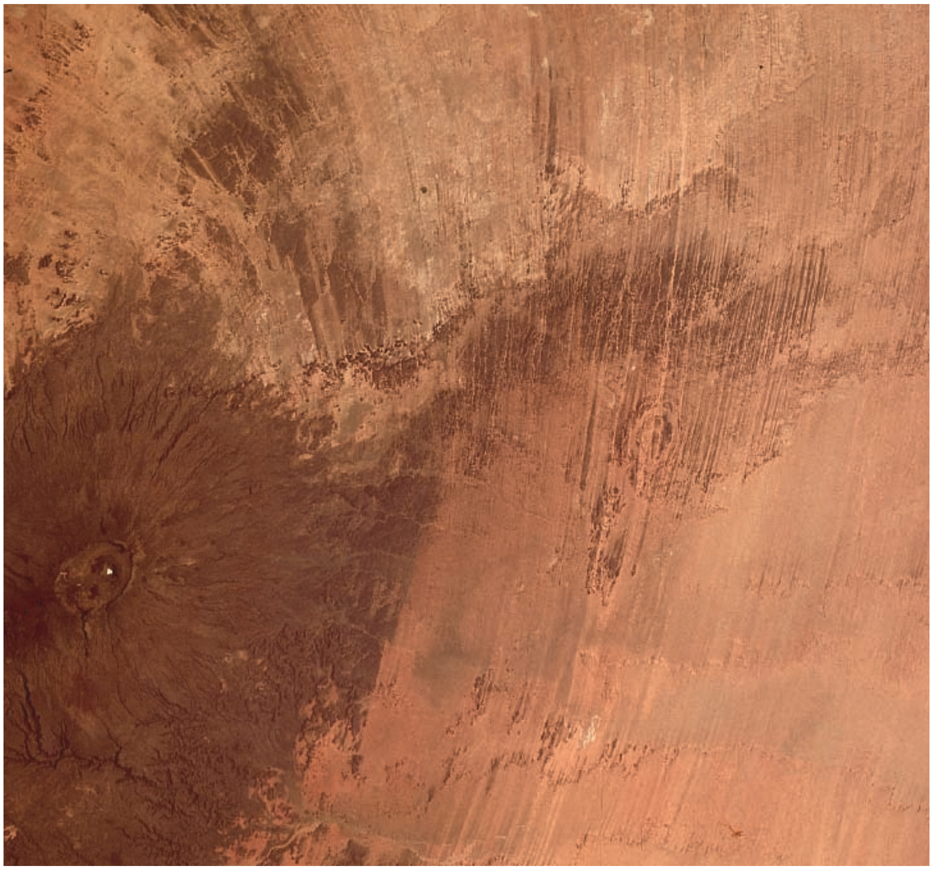


FIGURE 16.10 Yardangs and windstreaks in the Tibesti area of Chad are carved out of horizontally bedded nonresistant sedimentary rocks as regional winds are diverted around the eastern side of a large shield volcano. *(Courtesy of NASA)*

is only about 20 cm/sec (0.7 km/hr). Once entrained into the moving wind, a sediment particle moves in a variety of waves, which are similar to those in which sediment moves in water (Figure 16.11).

Saltation results from impact and elastic bounce (Figure 16.11). When a grain falls to the surface, it collides with other sand grains. The impact causes one or more grains to bounce into the air, where they are driven forward by the drag of the stronger wind above the surface. Gravity soon pulls them back, and the grains strike the ground at angles generally ranging from 10° to 15°. If the sand is moving over solid rock, the grains bounce back into the air. If the surface is loose sand, the impact of a falling grain can knock several grains into the air, setting up a chain reaction, which eventually sets in motion the entire sand surface. Saltation normally lifts sand grains less than 1 cm above the ground, but heights as much as a meter are not unusual. The forward velocity of saltating sand grains is usually about one-half the wind speed.

Wind Transportation

Some grains that are too large to be ejected into the flowing air move by surface **creep** (rolling and sliding). These large grains are moved by the impact of saltating grains and the drag of the wind, but they do not lose contact with the bed. Approximately one-fourth of the sand moved by a sandstorm travels by rolling and sliding. Particles with a diameter greater than 2 mm are rarely moved by wind.

Movement of Dust

If you have ever been in a dust storm, you know that the wind also carries fine sediment in another way. Small grains of dust (silt- and clay-sized particles with

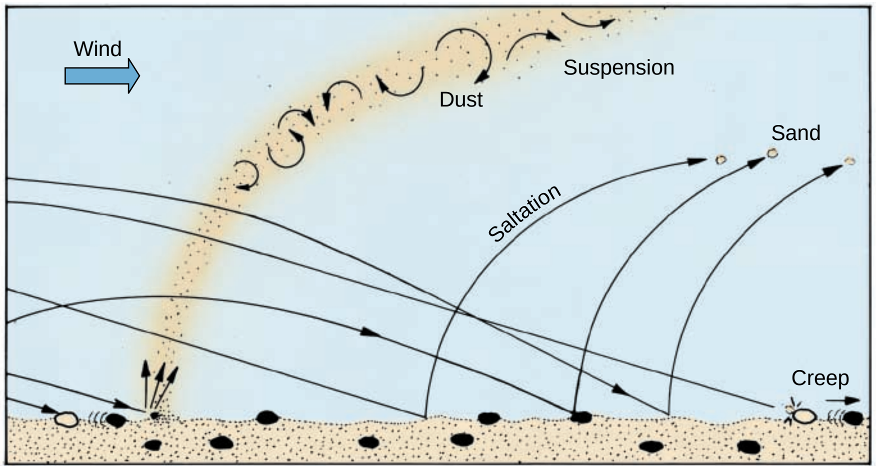


FIGURE 16.11 The transportation of sediment by wind is accomplished by surface creep, saltation, and suspension. Coarse grains move by impact from other grains and slide or roll (surface creep). Medium grains move by skipping or bouncing (saltation). Fine silt and clay move in suspension.

diameters of less than 0.06 mm) are carried in **suspension** by turbulence in the wind flow. Such particles are lifted high into the atmosphere and are carried great distances before they settle back to earth. Dust storms are major processes in deserts. They can transport thousands of tons of sediment hundreds of kilometers (Figure 16.12). Dust storms are a major dynamic process, and they subtly, but constantly, change the surface. Throughout human history, dust storms have been a major cause of soil erosion. References to dust storms were recorded in 1150 B.C. in China and in biblical times in the Middle East.

Dust Storms

Dust storms are commonly initiated by the downdraft of cool air from a cumulonimbus cloud. When such a cloud develops to the point that rain begins to fall from it, the rain cools the air as it falls. Because the cool air is denser than the surrounding air, it descends in a downdraft. As the heavy, cooled air reaches the ground, it is deflected forward and moves in a large tongue-shaped pattern. It flows across the ground as a density current—a body of moving air that is heavier than the surrounding air—because it is cooler (Figure 16.12). As the dense air moves

FIGURE 16.12 A dust storm in the Blue Nile area (Sudan, Africa) results when cool air descends and moves laterally over the surface as a density current. As the dense, cool air moves across the surface, it sweeps up dust and sand in its turbulent flow, creating a dust storm, or haboob. Eolian dust from such storms is an important component of deep-ocean sediment. *(Courtesy of Bruce Coleman, Inc.)*

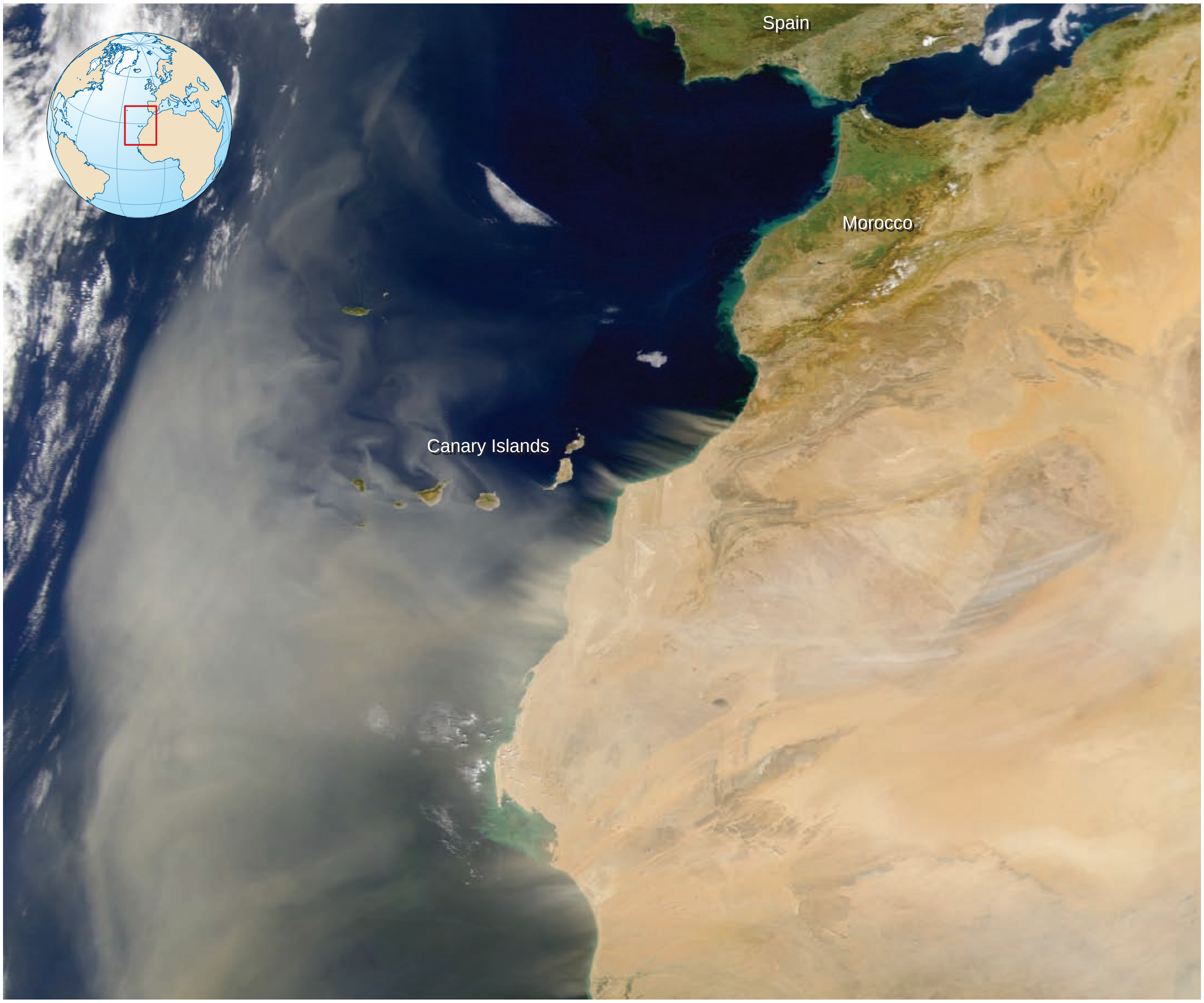


FIGURE 16.13 **Dust storms** in the Sahara Desert, as seen from a satellite. This storm formed by dissipating thunderstorms and then picked up loose sediment and moved it westward. The Canary Islands disturb the flow of the dust-laden winds. Storms like this can carry sediment into the Atlantic Ocean and as far west as the Americas. Eolian dust from such storms is an important component of deep-ocean sediment. *(Courtesy of NASA SeaWIFS Project)*

across the dry surface, it sweeps up dust and sand by the churning action of its turbulent flow. Dust storms of this type are called haboobs, from the Arabic word for "violent wind" (Figure 16.12).

Dust Storms

Great dust storms sometimes reach elevations of 2500 m and advance at speeds of up to 200 m/sec. It has been estimated that 500 million tons of wind-blown dust are carried from the deserts each year. (This is only slightly less than the amount of sediment deposited each year by the Mississippi River.) Some is deposited downwind from the desert, such as in China (Figure 16.1), but because of the prevailing wind pattern in the Sahara, Australia, and South America, large quantities of wind-blown dust are carried out to sea (Figure 16.13). Some larger dust storms in the Sahara have even carried dust across the Atlantic to the eastern coast of South America and the Caribbean Sea. Some diseases that afflict coral reefs around Florida and the Caribbean islands may have been carried there by such dust storms. A soil fungus that has caused an epidemic among some of the organisms in the coral reefs has been traced to central Africa.

DEPOSITS OF WIND-BLOWN SAND

Wind-blown sand accumulates to form sand sheets, ripples, and dunes. Different kinds of sand dunes result from variations in sand supply, wind direction, and velocity. The most significant types of dunes are (1) transverse dunes, (2) barchan dunes, (3) longitudinal dunes, (4) star dunes, and (5) parabolic dunes.

Where wind velocity decreases, moving sand grains may become deposited to form a variety of sedimentary bodies. About 40% of these deposits are gently undulating, nearly flat **sand sheets** (see Figure 16.19). Grains that are too big to move by saltation are the principal constituent, and many sand sheets grade into sand dunes. The active part of a sand sheet is only a few centimeters thick, but the sand sheet may cover a very large area. For example, much of southern Egypt and northern Sudan are covered by a featureless sand sheet.

Saltating grains form ripples that are perpendicular to the wind direction. The distance between each ripple is about the same as the average jump made by each saltating grain. These ripples are usually only a centimeter or so high. Ripples form on the surfaces of many dunes.

How can wind move an entire sand dune?

Sand dunes are the most commonly recognized deposits of sand. Dunes migrate relentlessly downwind and may completely modify the landscape, damaging or obliterating almost anything in their path. Forests have been entombed by advancing dunes, streams diverted, and villages completely covered (Figure 16.14). Examples of such migration occurred in England and France, where entire towns were overwhelmed by advancing dunes so that nothing was seen but the church spire. Then the dunes marched on, leaving behind a devastated countryside of dead trees and collapsed buildings. But why do dunes form, and why do some grow so large? How do they move?

In many respects, **dunes** are similar to ripple marks (formed by either air or water) and to the large sand waves or sandbars found in many streams and in shallow-marine water. Many dunes originate where an obstacle such as a large rock, a clump of vegetation, or a fence post creates a zone of quieter air behind it (Figure 16.15). As sand is blown up or around the obstruction and into the protected area (the wind shadow), its velocity is reduced and deposition occurs. Once a small dune is formed, it acts as a barrier itself, disrupting the flow of air and causing continued deposition downwind. Dunes range in size from 30 cm to as much as 500 m high and 1 km wide.

What is the difference in the way wind and water transport sediment?

(A) Dunes near Cairo, Egypt, encroach upon an apartment complex.

(B) Dune fields in northern Canada's polar desert migrate over a forest.

FIGURE 16.14 **Migrating sand dunes** may obliterate or damage almost anything in their path. These dunes in North Africa and North America are gradually inundating buildings and forests.

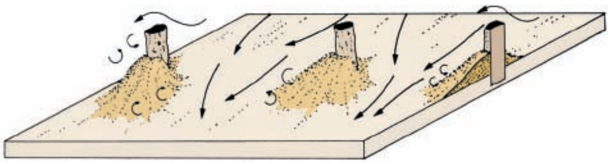


FIGURE 16.15 Sand dunes commonly originate in wind shadows. Any obstacle that diverts the wind, such as a bush or a fence post, creates eddies and reduces wind velocity. Wind-blown sand is deposited in protected areas, and eventually enough sand accumulates in the wind-shadow area to form a dune. The dune itself then acts as a barrier, making its own wind shadow, and thus causes additional accumulation of sand.

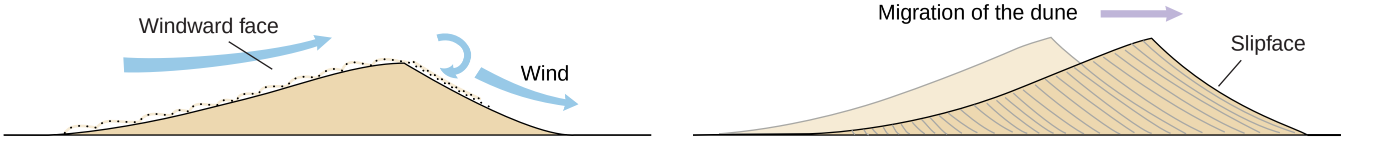


FIGURE 16.16 A sand dune migrates as sand grains move up the slope of the dune and accumulate in a protected area on the downwind face. The dune slowly moves grain by grain. As the grains accumulate on the downwind slope, they produce a series of layers (cross-beds) inclined in a downwind direction. *(Photograph by E. McKee, U.S. Geological Survey)*

FIGURE 16.17 **Cross-bedding** in the Navajo Sandstone in Zion National Park, Utah, is evidence that the rock formed in an ancient desert. The inclination of the strata shows that the wind blew from north to south (from left to right, in the photograph) for most of the time during which this formation was being deposited.

The movement of sand in a typical dune is diagrammed in Figure 16.16. A typical dune is asymmetrical, with a gently inclined windward slope and a steeper downwind slope—the **lee slope,** or **slip face.** The steep slip face of the dune shows the direction of the prevailing wind. Dunes migrate grain by grain as wind transports sand by saltation and surface creep up the windward slope. The wind continues upward past the crest of the dune, creating divergent airflow and eddies just over the lee slope. Beyond the crest, the sand drops out of the wind stream and accumulates on the slip face. When the sand grains exceed the angle of repose, they spill down the slip face in small landslides or avalanches. As more sand is transported from the windward slope and accumulates on the lee slope, the dune migrates downwind. The internal structure of a migrating dune consists of **cross-beds** formed as the saltating grains accumulate on the inclined downwind slope of the dune (Figure 16.16). Strata formed on the lee slope are therefore inclined downwind. Geologists map the directions of ancient winds by measuring the directions in which the cross-strata of wind-blown sandstone are inclined (Figure 16.17).

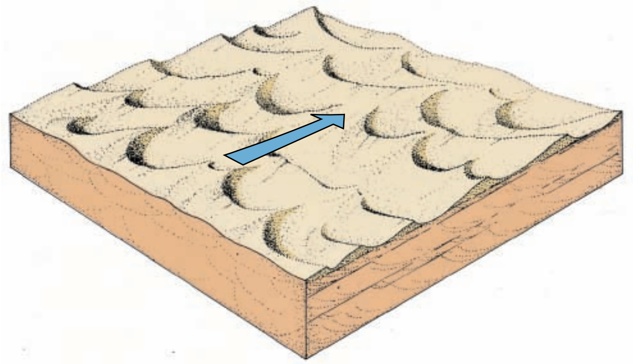
Why do sand dunes assume different shapes?

Quartz is the most common mineral in wind-blown sand because of its hardness, strength, and resistance to weathering. In some areas, gypsum also forms sand-sized grains that can saltate and accumulate in dunes.

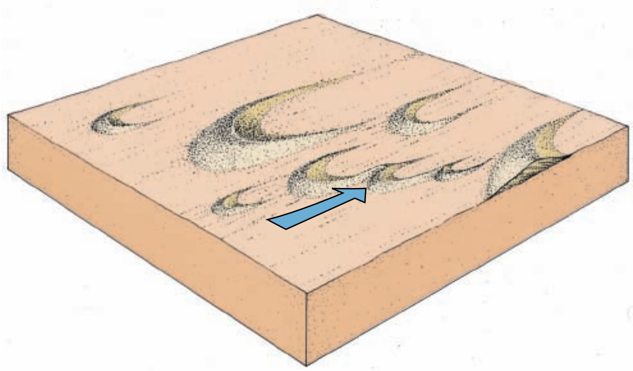
Types of Sand Dunes

Sand dunes vary greatly in size and shape, and although they form bleak and barren wastelands, they impart a sense of stark beauty and hidden mysteries to the areas they cover.

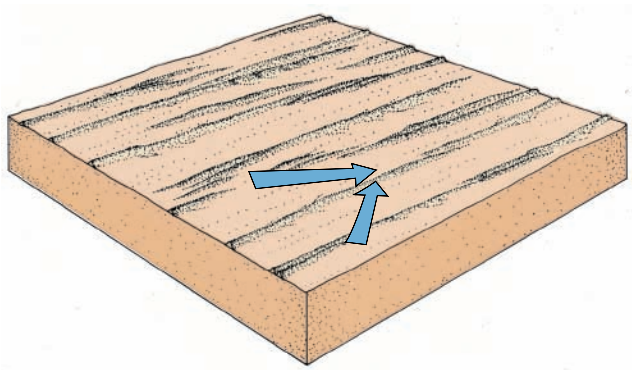
Transverse dunes typically develop where there is a large supply of sand and a constant wind direction (Figure 16.18A). These dunes cover large areas and develop wavelike forms, with sinuous ridges and troughs, perpendicular to the prevailing



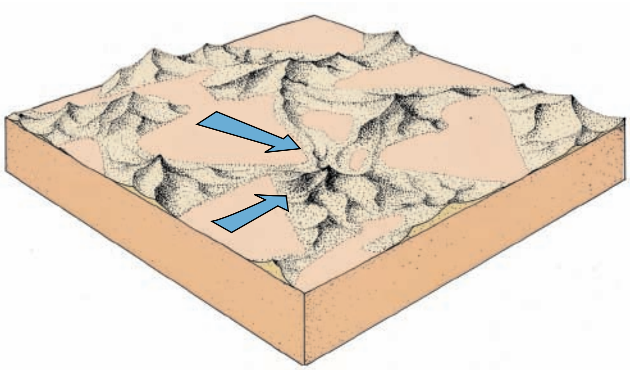
(A) Transverse dunes develop where the wind direction is constant and the sand supply is large.



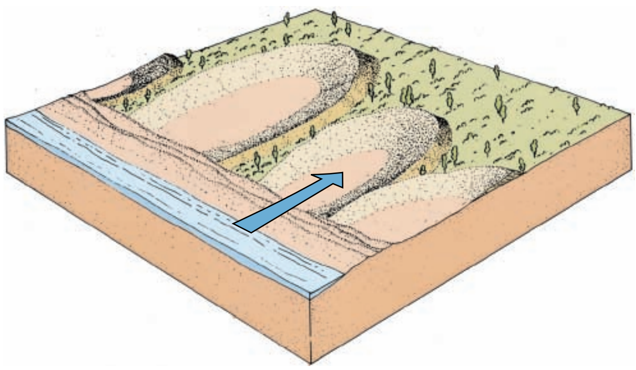
(B) Barchan dunes develop where the wind direction is constant but the sand supply is limited.



(C) Linear or seif dunes are formed by converging winds in an area with a limited sand supply.



(D) Star dunes develop where the wind direction is variable.



(E) Parabolic dunes are formed by strong onshore winds.

FIGURE 16.18 Each of the major types of sand dunes represents a unique balance between sand supply, wind velocity, and variability in wind direction. The arrows show the major wind directions.

wind. Transverse dunes commonly form in deserts where exposed ancient sandstone formations provide an ample supply of sand. They usually cover large areas known as sand seas, so called because the wavelike dunes produce a surface resembling that of a stormy sea (Figure 16.19).

Barchan dunes form where the supply of sand is limited and winds of moderate velocity blow in a constant direction (Figure 16.18B). These crescent-shaped dunes are typically small, isolated dunes from 1 to 50 m high. The tips (or horns) of a barchan point downwind, and sand grains are swept around them as well as up and over the crest. With a constant wind direction, beautiful symmetric crescents form. With shifts in wind direction, however, one horn can become larger than the other. Although barchans typically are isolated dunes, they may be arranged in a chainlike fashion, extending downwind from the source of sand.

FIGURE 16.19 **Sand seas in south Africa** have been mapped with the use of satellite photography. A sand sea covers much of Namibia where some of Earth's highest sand dunes are found. Some are as much as 300 m high. A variety of dune types are formed as a result of variations in wind velocity and direction, supply of sand, and the nature of the surface over which the sand moves. This image shows an area about 100 km across. *(Courtesy of U.S. Geological Survey and Eros Data Center)*

Linear dunes or **seif dunes** (Arabic, "sword") are long, parallel ridges of sand, elongate in a direction parallel to the vector resulting from two slightly different wind directions (Figure 16.18C). They develop where strong prevailing winds converge and blow in a constant direction over an area having a limited supply of sand. Many linear dunes are less than 4 m high, but they can extend downwind for several kilometers. In larger desert areas, they can grow to 100 m high and 120 km long, and they are usually spaced from 0.5 to 3 km apart. Linear dunes occupy a vast

FIGURE 16.20 **Ancient sand seas** are evidenced by thick deposits of wind-blown sand in the Colorado Plateau and adjacent regions of the western United States. During the early Mesozoic Era, this region was a vast dry plain where eolian sands accumulated in a subsiding basin. This photograph of the White Cliffs in the Grand Staircase is typical of the deposits of more than five major sand seas now preserved in the rock record.

area of central Australia called the Sand Ridge Desert. They are especially well developed in some desert regions of North Africa and the Arabian Peninsula.

Star dunes are mounds of sand having a high central point, from which three or four arms, or ridges, radiate (Figure 16.18D). This type of dune is typical in parts of North Africa and Saudi Arabia. The internal structure of these dunes suggests that they were formed by winds blowing in three or more directions. Some are 500 m high.

Parabolic dunes (blowouts) typically develop along coastlines where vegetation partly covers a ridge of wind-blown sand, transported landward from the beach (Figure 16.18E). Where vegetation is absent, small deflation basins are produced by strong onshore winds. These blowout depressions grow larger as more sand is exposed and removed. Usually, the sand piles up on the lee slope of the shallow deflation hollow, forming a crescent-shaped ridge. In map view, a parabolic dune is similar to a barchan, but the tips of the parabolic dune point upwind and are fixed in place by vegetation. Because of their form, parabolic dunes are also called hairpin dunes.

Sand Seas

Although Earth is commonly called the water planet, several continents have vast areas where precipitation is rare, and the surface is covered with wind-blown sand. Some of these areas are so vast they are known as **sand seas,** or **ergs** (Figure 16.19). It has been calculated that 99.8% of all wind-blown sand is in the great sand seas of the world. The largest are in Africa, Asia, and Australia. In Africa, about 800,000 km^2 (or one-ninth of the entire area of the Sahara) is covered by stable or active sand dunes. One-third of Saudi Arabia, approximately 1,000,000 km^2, is covered by eolian sand, and in the vast Rub' al Khali (Empty Quarter), dunes may be more than 200 m high and cover about 400,000 km^2. The Australian sand seas are mainly in the western and central portions of that continent (Figure 16.1). Dunes cover most of the area (about 60%) of a typical sand sea; the rest consists of sand sheets.

Ancient Sand Seas. Sand deposits from ancient deserts are found in many parts of the world, including those where deserts do not exist today. These ancient sand seas are distinctive sedimentary deposits with a texture (cross-bedded) and composition (clean quartz sand) that reveals their origin. They range in age from a few thousand to more than 500 million years old and provide an important record of climatic change and movement of tectonic plates.

FIGURE 16.21 **Loess deposits in central China** cover vast areas and are exceptionally thick. They illustrate the typical properties of loess, including fine grain size, sequences of buried soils, buff color, and steep cliff faces.

Some ancient sand seas indicate that climatic conditions have changed considerably over vast areas. For example, the Sand Hills of Nebraska are an inactive dune field covering some 57,000 km^2. The dunes were active during the last ice age, which ended about 15,000 years ago. Barchan and transverse types are well preserved; some are 120 m high. Because of climate change during the last interglacial period, they are now covered with grass and do not migrate.

Other sand seas developed when moving continents drifted through the low-latitude zones where deserts form. Such is the case for those in western North America. Ancient sand seas were especially numerous and widely distributed throughout the western United States during late Paleozoic and Mesozoic time. More than eight formations of eolian sand have been recognized, and much of the spectacular scenery of the Colorado Plateau is developed in these colorful strata (Figure 16.20). The formations are typically white, buff, or pale red, and they erode into steep cliffs. Many national parks and monuments including Zion, Capitol Reef, Canyonlands, Arches, Canyon de Chelly, and the Grand Canyon expose formations developed in ancient sand seas. Ancient wind directions can easily be determined by the dip direction of the cross-strata. It is thus possible to map patterns of ancient winds when the sandstone formations were being deposited. These great accumulations of sand record the passage of North America through the dry desert latitudes during the late Paleozoic and Mesozoic Eras.

DEPOSITS OF WIND-BLOWN DUST: LOESS

Loess is a deposit of wind-blown dust (silt and clay) that accumulates slowly and ultimately blankets large areas. It covers one-tenth of the world's present land surface. The dust is derived either from nearby deserts or from rock flour originating near recently glaciated regions. Wind-blown dust settles in the oceans and is an important source of deep-marine mud.

Wind-blown dust may accumulate in thick deposits called **loess** (German, "loose") that blankets many regions throughout the world. Loess is a distinctive sediment. It is composed mostly of silt-size grains, but smaller clay-size grains are also common. Loess is typically yellowish brown and is composed of small angular grains of quartz, feldspar, and clay. Although it is loose, friable, and porous, it typically erodes into vertical walls that do not crumble unless they are disturbed. As the dust accumulates, successive generations of grass roots (now

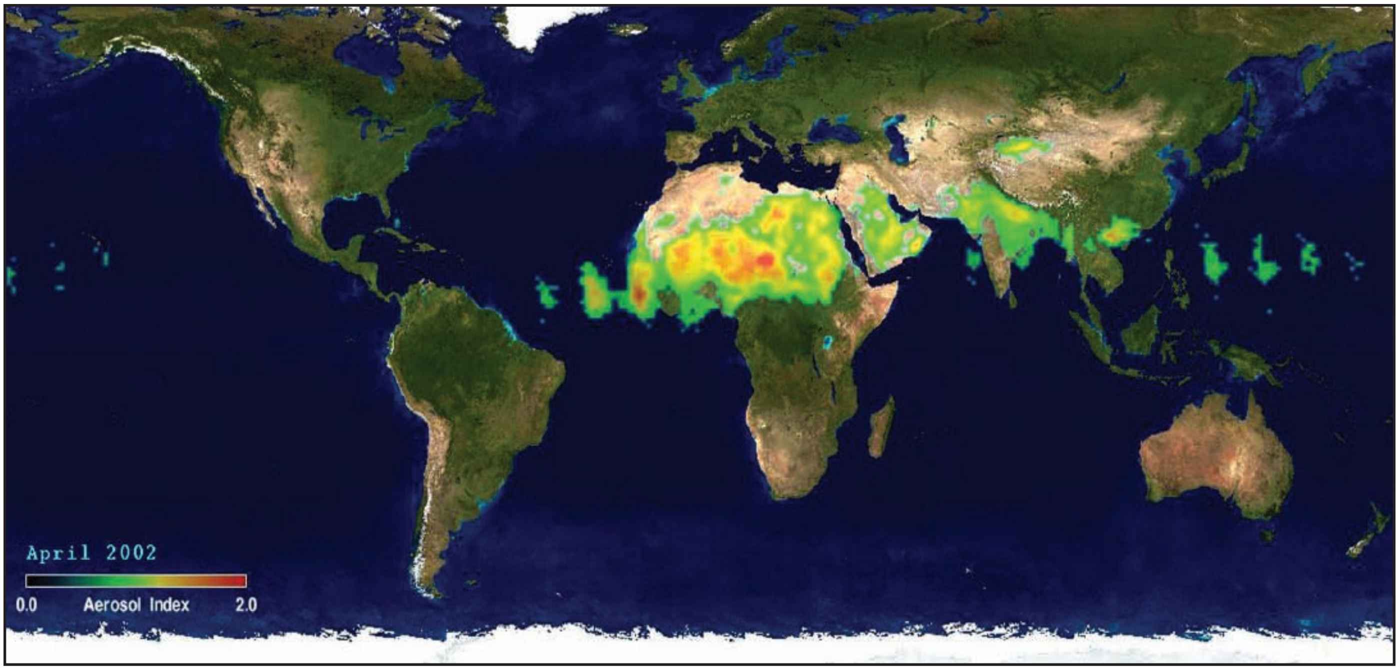


FIGURE 16.22 **Dust sources and distribution paths** are shown for April 2002. They are based on satellite measurements of aerosols in the atmosphere. Most dust is derived from the deserts of Arabia and north Africa and then blown toward the Atlantic by prevailing winds. Dust plumes are also common north and south of the Himalaya mountains. *(Courtesy of J. Herman, Laboratory for Atmospheres, Goddard Space Flight Center)*

represented by narrow tubes partly filled with calcium carbonate) make it sufficiently coherent to stand up in vertical cliffs (Figure 16.21).

What geologic features are produced by wind-blown dust?

Dust is dispersed high into the atmosphere and carried great distances by the wind (Figure 16.22). Therefore, loess is widespread beyond desert areas and, unlike sand dunes, loess deposits blanket the landscape, covering hills and valleys alike. The map in Figure 16.1 shows the distribution of loess. Loess covers as much as one-tenth of Earth's land surface and is particularly widespread in semiarid regions along the margins of the great deserts between latitude 24° to 55° north and 30° to 45° south. Equatorial regions are free from loess because as soon as dust accumulates, it is washed away by heavy rainfall. Areas formerly covered by continental glaciers are also free from loess because glaciated terrains are new surfaces that were covered with ice until only a few thousand years ago. Loess is not widespread in the major desert regions because dust is swept out of the deserts and deposited in adjacent areas.

Asian Dust

As can be seen in Figure 16.22, the global dispersion of wind-blown dust is related to the prevailing wind patterns in the major desert regions of the world. Wind carries dust from the deserts of central Asia to the south and east, where it is deposited over vast areas of China. The greatest deposits of loess are in the Shansi and adjacent provinces of China, where it locally exceeds 300 m in thickness. Over immense areas, many meters of dust have accumulated, completely burying the entire landscape (Figure 16.23). From the deserts of North Africa, dust is carried by the prevailing winds to the west, where it settles out over the Atlantic Ocean. Oceanographic research has identified wind-blown dust that forms distinctive widespread layers on the seafloor. Indeed, wind-blown dust is an important source of deep-marine mud. Some dust from the Sahara is blown northward and is trapped in the Mediterranean Sea, but occasionally some reaches southern Europe and has been known to turn white Alpine snow into delicate shades of pink and brown.

Most of the great loess deposits of North America and Europe are not related to desert dust but are considered to have their sources in the outwash plains of continental glaciers. Rock debris pulverized and transported by glaciers is

FIGURE 16.23 **Young loess deposits in northern China** are as much as 100 m thick and are widely used for agriculture. Stream erosion has cut deep valleys, but there is still a tendency to stand in vertical cliffs. Inasmuch as the loess forms an excellent soil, it can be terraced for optimum agricultural production.

ultimately deposited as glacial outwash. This sediment, commonly called rock flour, was then picked up by strong thermal winds moving down off the glacier. These winds carried the fine particles aloft and then deposited them as a blanket of loess beyond the margins of the ice. In the central United States, most of the loess is in the uplands of the Mississippi drainage system and is well exposed as vertical cliffs along the riverbanks. Near rivers where floodplain muds provide a ready source of dust, the loess is 30 m or more thick, but it thins out away from the river channels. The greatest accumulations are east of the floodplains; their thickness is controlled by the prevailing winds.

In Eurasia, a long belt of loess derived from glacial material stretches from France to China (Figure 16.1). Beginning as local thin patches in France and Germany, the deposits become thicker and more extensive as they are traced across Russia and Turkestan.

Loess has played an important role in human history, and it continues to be highly significant today. Loess forms some of the most productive soils in the world;

FIGURE 16.24 **Loess plateaus of China** are highly dissected into an intricate network of tributaries to the Yellow River, so-named because of the abundance of fine sediment in the river.

the steppes of eastern Europe (the Ukraine and Russia) and the plains of the midwestern United States are all blanketed by loess (Figure 16.1). This correlation is not by chance. Loess is not deposited in dry desert regions but in adjacent areas where there is enough precipitation to support agriculture. It is transported, not decomposed, soil and is rich in nutrients because they have not been leached away. Moreover, because it is transported soil, it is commonly thicker and not as easily stripped away as relatively thin weathered soils.

Long before the Qin (Ch'in) dynasty in 221 B.C., farming was initiated on the loess plains of northern China. This exceptional soil, blown in from the Gobi Desert during the ice age, shaped the origins of China. On this rich land along the middle Yellow and Wei rivers, the first Chinese culture developed in the fifth millennium B.C. The fertility of the soil when irrigated led to the development of the remarkable water control work of ancient China. The loess in China is up to 335 m thick and covers an area of more than 400,000 km^2. This soft, loose fine material is easily eroded and is carved into a remarkable maze of dendritic stream valleys (Figure 16.24). In this region, everything is yellow: the land, the homes, and the water. It is loess that gives the name to the Yellow River, whose sediment load is simply loess remobilized by water. In fact, the Yellow River is more like a thin mudflow than like running water. The loess in the Yellow River is ultimately delivered to the ocean, where much stays in suspension for a long time, imparting its characteristic color to the Yellow Sea.

DESERTIFICATION

> Desertification (or land degradation) occurs naturally or as a result of the activities of people. Exploitation and overgrazing of sensitive lands adjacent to natural deserts can cause a desert to expand.

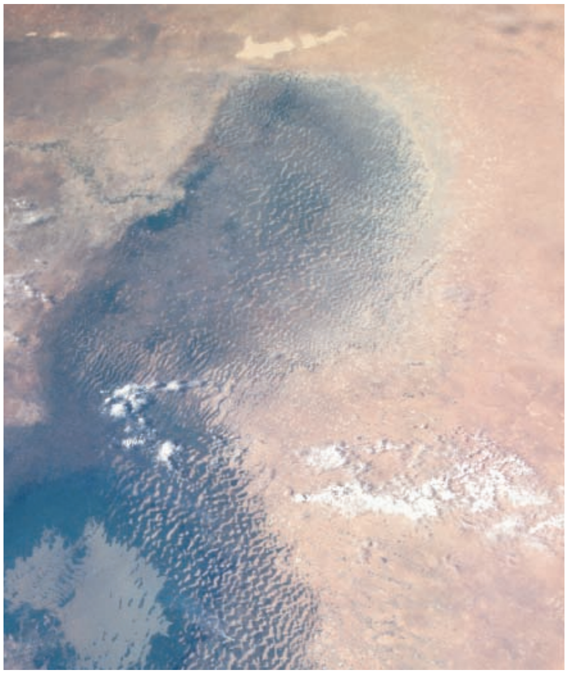
The great deserts of the world formed by natural processes over long periods, as continents migrated into dry climates produced in low-latitude, high-pressure zones. A desert may expand and shrink in response to short-term cyclic climatic fluctuations. The margins of deserts, therefore, have always been transitional or gradational to the adjacent, more humid environments.

There are two distinct forms of desert expansion. One is a natural process due to climatic change or the migration of moving sand. It takes place on the immediate edges of existing deserts, and when the distribution of rain over the desert and surrounding areas shifts, the desert expands or contracts. Some desert expansion takes place over thousands of years.

The second form of desertification results from human-induced breakdown of soils in the zones adjacent to deserts. Poor cultivation practices, overgrazing, and deforestation are the major causes. Sparse vegetation inhibits wind erosion, but when it is destroyed, the desert expands. Along the desert margins, human activity is commonly superimposed upon the natural processes that cause the expansion and contraction of the deserts. Grazing livestock, the compaction of soil by hooves, and even the collection of firewood by humans can reduce the plant cover. The soil ultimately degrades, and, in many cases, the desert expands. This process, in which productive land becomes unproductive, is called **land degradation** or **desertification.** If the general climatic trend is toward increasing aridity, desertification can occur with remarkable speed. This type of desertification results when the number of people and livestock exceeds the capacity of the rainfall to supply their food.

Desertification does not occur in a broad, even swath that can easily be mapped along the desert fringe. Deserts advance erratically, forming patches on their borders, and areas far from the desert may quickly degrade into barren rock and sand. Desertification presents an enormous problem for human existence. About one-third of Earth's land is arid or semiarid, but only about one-half of this area

(A) Lake Chad 1966.



(B) Lake Chad 1992.

FIGURE 16.25 **Lake Chad** is a shallow freshwater lake between the Sahara Desert and the tropics. Climatic variations cause the lake to expand or shrink. During the ice age, the lake covered 1,000,000 km^2. In 1966 (A) the lake covered only 25,000 km^2. The nose of the *Gemini* spacecraft covers the lower part of the photo. The lake shrank to 1200 km^2 during the drought of the Sahel in 1992 (B). Fishing villages once on the shore are now stranded many kilometers from water. *(Digital image copyright 1996 Corbis; original image courtesy of NASA)*

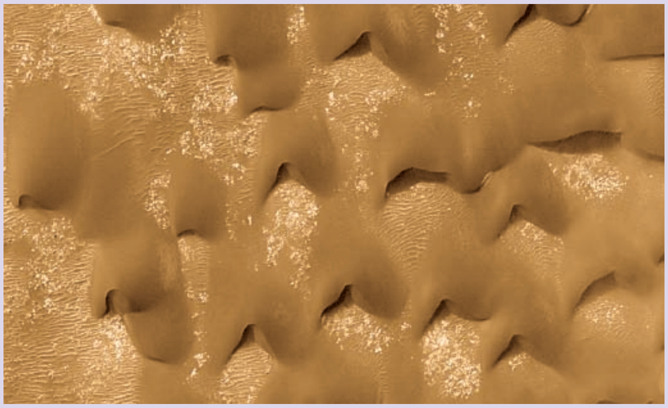
is so dry that it cannot support human life. More than 600 million people live in the dry areas, and about 80 million live on land that is nearly useless because of desertification. The most severe problems are in Africa and Asia. The United Nations estimates that more than 11 billion acres (35% of the world's cropland) show signs of human-induced degradation.

The Sahel, a semiarid zone south of the Sahara Desert, is commonly used as an example of desertification. It extends across the entire continent of Africa and includes Ethiopia, the Sudan, Mauritania, and all of the small countries in between. It is a transition zone, 800 to 1000 km wide, separating the Sahara to the north from the well-watered grasslands of central Africa. The area receives rainfall from the seasonal northward shift of moist equatorial air masses, but it suffers a long, hot, rainless season that is the result of dry northeasterly trade winds blowing southward out of the Sahara. A slight shift in the wind patterns causes significant changes in climate and weather. An example of these changes can be seen in the shrinking shoreline of Lake Chad (Figure 16.25). This natural situation, combined with overgrazing, removal of trees for firewood, and an annual population growth rate of 2.5% to 3.0%, have stressed the Sahel's sensitive environment. Drought and human suffering go hand in hand in this fragile area.

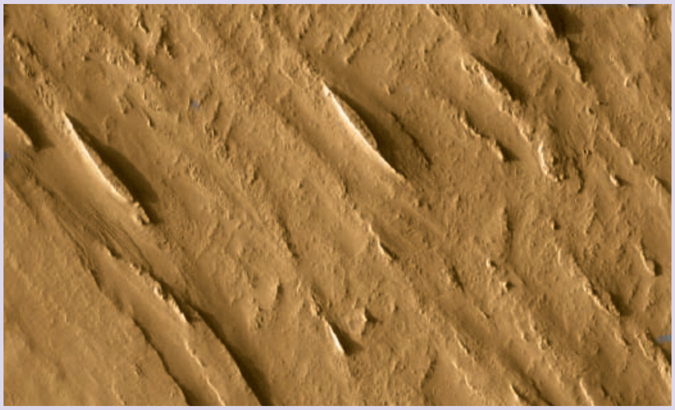
Lake Chad

Clearly, neither shipping emergency food nor drilling more and deeper wells are the answers to desertification. Reaction to disaster must be replaced by predisaster planning, based on a clear understanding of an area's basic geologic systems and of the kinds of changes that occur naturally.

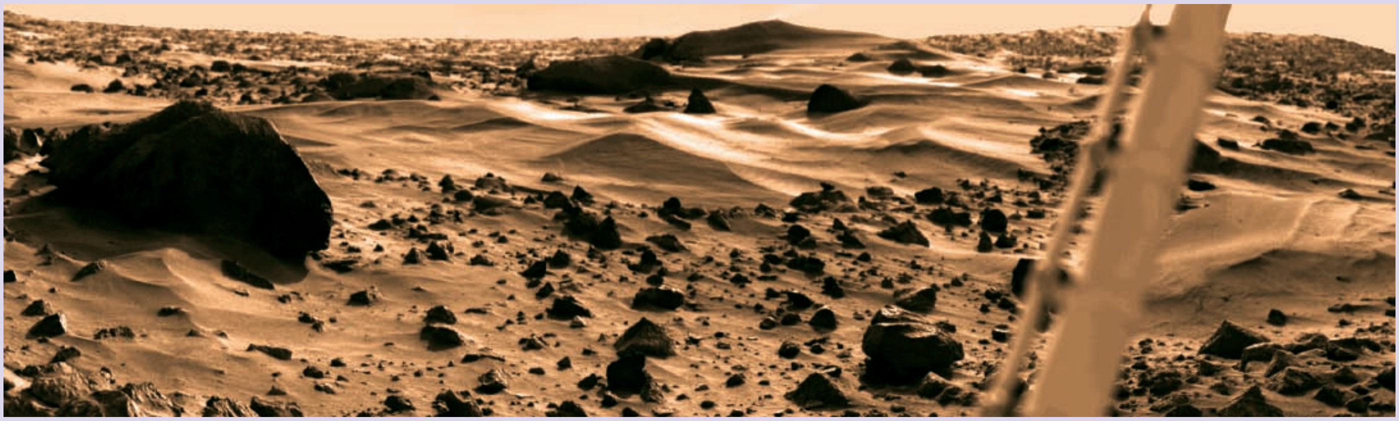
GeoLogic Mars: The Eolian Planet



(A) Sand dunes like these barchans are very common on Mars. (*Courtesy of NASA and Malin Space Science Systems)*



(B) Yardangs emanate from incompletely stripped hills. (*Courtesy of NASA and ASU Themis Science Team)*



(C) The surface of Mars is dominated by eolian erosion and deposition. Small dunes have formed from saltating sand. The wind has also fluted some pebbles and scoured away loose sediment leaving a lag of pebbles and boulders. (*Courtesy of NASA)*

Mars is the fourth planet from the Sun. Its surface temperature and atmospheric pressure are both much lower than on Earth. So low, that liquid water is not stable at the present time. It either vaporizes or freezes. How has this modified the surface of Mars?

Observations

1. Occasionally global dust storms envelope the entire planet, obscuring the peaks of volcanoes that are 20 km high.
2. Winds comparable to those in a strong hurricane on Earth rage for several months at a time.
3. Windstreaks caused by erosion and deposition are found near many impact craters.
4. Dunes are found in almost all regions on Mars. The largest sand sea encircles the polar ice cap and is comparable in size to the entire Sahara Desert. Long transverse dunes break up into isolated barchans on the margin of the erg.
5. Yardangs have developed by abrasion of young deposits that are weakly consolidated and long narrow spines project from low plateaus, The ridges are narrow and keellike, and the ends taper sharply. Their alignment shows the dominant wind direction
6. Irregular blankets of loess mantle most of the planet and are interlayered with ice in the polar ice caps.
7. On the surface, landers have photographed small sand dunes. The blocky, angular rocks that mantle the area resemble desert pavement Some of the rocks are fluted and shaped into ventifacts, as if eroded by the wind.

Interpretations

These features collectively show that Mars is a cold desert where the wind is the dominant active process. Everywhere you look the surface is shaped by the wind. The wind is constantly moving and redepositing loose surface material. If not for its liquid water and abundant plant life, Earth too would be an eolian planet. Which processes do you think are more common in our solar system—those driven by wind or those caused by running liquid water?

KEY TERMS

barchan dune (p. 468)
blowout (p. 470)
Coriolis effect (p. 456)
creep (p. 462)
cross-bed (p. 467)
deflation (p. 458)
deflation basin (p. 458)
desertification (p. 474)
desert pavement (p. 459)
drag (p. 461)
dune (p. 465)
erg (p. 470)
lag deposit (p. 459)
land degradation (p. 474)
lee slope (p. 467)
lift (p. 461)
linear dune (p. 469)
loess (p. 471)
parabolic dune (p. 470)
rain shadow (p. 456)
saltation (p. 462)
sand sea (p. 470)
sand sheet (p. 465)
seif dune (p. 469)
slip face (p. 467)
star dune (p. 470)
suspension (p. 463)
transverse dune (p. 467)
ventifact (p. 459)
yardang (p. 459)

REVIEW QUESTIONS

1. Describe the processes involved in wind erosion.
2. What controls the distribution of the major desert regions of Earth?
3. What landforms are produced by wind erosion and deflation?
4. Explain the origin of ventifacts.
5. Explain the origin of desert pavements.
6. Draw a simple diagram showing how sand is transported by wind.
7. Why is wind an effective agent in sorting sand and dust?
8. Describe how a sand dune forms and how it migrates.
9. List the five major types of dunes, and state the conditions under which each type forms (wind direction and velocity, sand supply, and the characteristics of the surface over which the sand moves).
10. What is the origin of loess?
11. Where are the major areas of loess deposits in the world today?
12. What changes in the Australian desert would occur if that continent were to drift 2000 km (approximately 20° of latitude) northward?

ADDITIONAL READINGS

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MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Video showing how sand is transported in a wind tunnel
- Animations of the circulation of the atmosphere that creates deserts
- Slide shows with more examples of loess
- A direct link to the Companion Website