Deserts and Winds

CHAPTER

19

Arizona's Organ Pipe Cactus National Monument is in the Sonoran Desert. Ajo Mountains in the background. (Photo by Jeff Lepore/Photo Researchers, Inc.)

Climate has a strong influence on the nature and intensity of Earth's external processes. This was clearly demonstrated in the preceding chapter on glaciers. Another excellent example of the strong link between climate and geology is seen when we examine the development of arid landscapes. The word *desert* literally means deserted or unoccupied. For many dry regions this is a very appropriate description, although where water is available in deserts, plants and animals thrive. Nevertheless, the world's dry regions are probably the least familiar land areas on Earth outside of the polar realm.

Desert landscapes frequently appear stark. Their profiles are not softened by a carpet of soil and abundant plant life. Instead, barren rocky outcrops with steep, angular slopes are common. At some places the rocks are tinted orange and red. At others they are gray and brown and streaked with black. For many visitors, desert scenery exhibits a striking beauty; to others, the terrain seems bleak. No matter which feeling is elicited, it is clear that deserts are very different from the more humid places where most people live.

As you will see, arid regions are not dominated by a single geologic process. Rather, the effects of tectonic forces, running water, and wind are all apparent. Because these processes combine in different ways from place to place, the appearance of desert landscapes varies a great deal as well (Figure 19.1).

FIGURE 19.1 A scene in Southern Utah near the San Juan River. The appearance of desert landscapes varies a great deal from place to place. (Photo © by Carr Clifton. All rights reserved.)

Distribution and Causes of Dry Lands

Deserts and Winds
▸ **Distribution and Causes of Dry Lands**

The dry regions of the world encompass about 42 million square kilometers, a surprising 30 percent of Earth's land surface. No other climatic group covers so large a land area. Within these water-deficient regions, two climatic types are commonly recognized: **desert,** or arid, and **steppe,** or semiarid. The two share many features; their differences are primarily a matter of degree (see Box 19.1). The steppe is a marginal and more humid variant of the desert and is a transition zone that surrounds the desert and separates it from bordering humid climates. The world map showing the distribution of desert and steppe regions reveals that dry lands are concentrated in the subtropics and in the middle latitudes (Figure 19.2).

Low-Latitude Deserts

The heart of the low-latitude dry climates lies in the vicinities of the Tropics of Cancer and Capricorn. Figure 19.2 shows a virtually unbroken desert environment stretching for more than 9300 kilometers (5800 miles) from the Atlantic coast of North Africa to the dry lands of northwestern India. In addition to this single great expanse, the Northern Hemisphere contains another, much smaller area of tropical desert and steppe in northern Mexico and the southwestern United States.

Students Sometimes Ask . . .

I thought that deserts are generally lifeless places. Is this true?

Although this is a common misconception, deserts do have sparse—and in some cases abundant—life. Plants and animals that live in deserts have special adaptations for surviving in these arid environments, most notably a highly developed tolerance of drought. For instance, many desert plants have waxy leaves, stems, or branches or a thickened cuticle (outermost protective layer) to reduce water loss. Others have very small leaves or no leaves at all.

Also, the roots of some species often extend to great depths in order to tap the moisture found there, whereas others produce a shallow but widespread root system that enables them to absorb large amounts of moisture quickly from the infrequent desert downpours. Often the stems of these plants are thickened by a spongy tissue that can store enough water to sustain the plant until the next rainfall comes. Thus, although widely dispersed and providing little ground cover, plants of many kinds flourish in the desert.

Animals are also superbly adapted to life in the desert. Many are nocturnal and come out only during the cool of night. Some, like the kangaroo rat, never need to drink water. Instead, they get all the water they need from what they eat. Others can hibernate for many months and are active only after sufficient rain has fallen. Deserts are home to a wide variety of organisms.

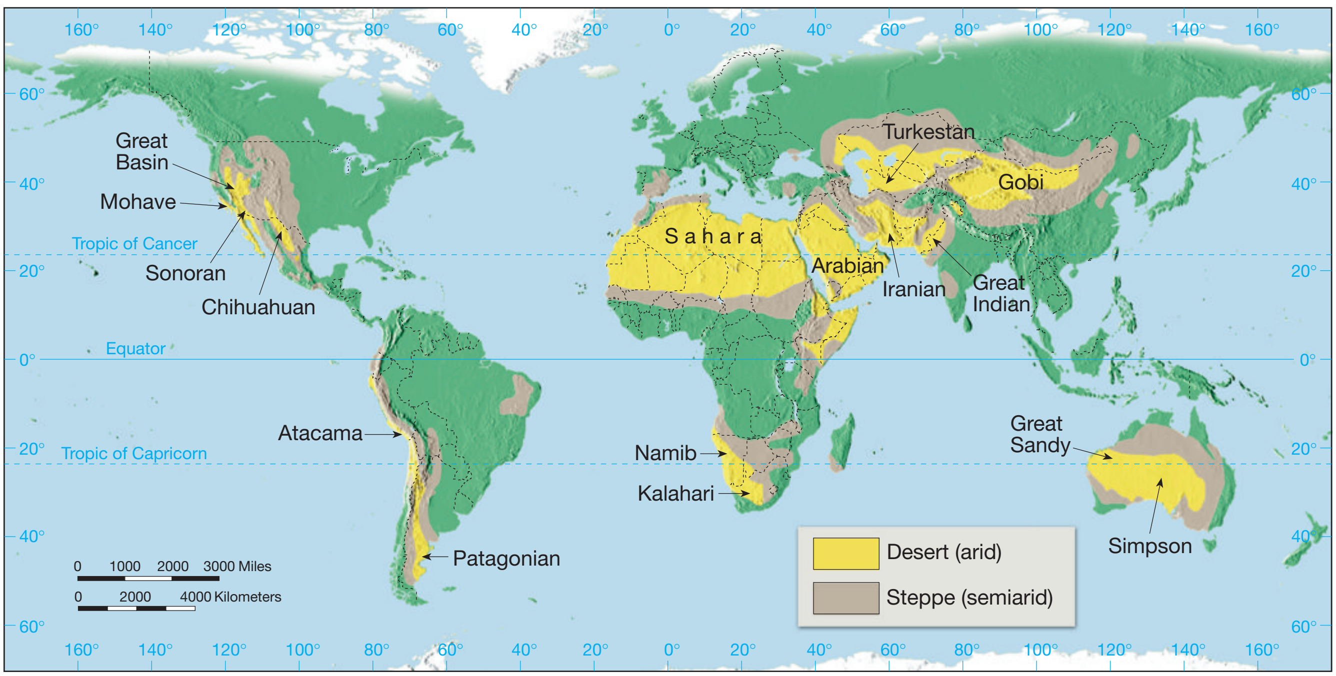


FIGURE 19.2 Arid and semiarid climates cover about 30 percent of Earth's land surface. No other climate group covers so large an area.

BOX 19.1 ▶ UNDERSTANDING EARTH

What Is Meant by "Dry"?

Albuquerque, New Mexico, in the southwestern United States, receives an average of 20.7 centimeters (8.07 inches) of rainfall annually. As you might expect, because Albuquerque's precipitation total is modest, the station is classified as a desert when the commonly used Köppen climate classification is applied. The Russian city of Verkhoyansk is a remote station located near the Arctic Circle in Siberia. The yearly precipitation total there averages 15.5 centimeters (6.05 inches), about 5 centimeters less than Albuquerque's. Although Verkhoyansk receives less precipitation than Albuquerque, its classification is that of a humid climate. How can this occur?

We all recognize that deserts are dry places, but just what is meant by the term *dry*? That is, how much rain defines the boundary between humid and dry regions? Sometimes it is arbitrarily defined by a single rainfall figure, for example, 25 centimeters (10 inches) per year of precipitation. However, the concept of dryness is a relative one that refers to any situation in which a water deficiency exists. Hence, climatologists define *dry climate* as one in which yearly precipitation is not as great as the potential loss of water by evaporation. Dryness, then, not only is related to annual rainfall totals but is also a function of evaporation, which in turn is closely dependent upon temperature.

As temperatures climb, potential evaporation also increases. Fifteen to 25 centimeters of precipitation may be sufficient to support coniferous forests in northern Scandinavia or Siberia, where evaporation into the cool, humid air is slight and a surplus of water remains in the soil. However, the same amount of rain falling on New Mexico or Iran supports only a sparse vegetative cover because evaporation into the hot, dry air is great. So, clearly, no specific amount of precipitation can serve as a universal boundary for dry climates.

To establish the boundary between dry and humid climates, the widely used Köppen classification system uses formulas that involve three variables: average annual precipitation, average annual temperature, and seasonal distribution of precipitation. The use of average annual temperature reflects its importance as an index of evaporation. The amount of rainfall defining the humid–dry boundary will be larger where mean annual temperatures are high, and smaller where temperatures are low. The use of seasonal precipitation distribution as a variable is also related to this idea. If rain is concentrated in the warmest months, loss to evaporation is greater than if the precipitation is concentrated in the cooler months.

Table 19.A summarizes the precipitation amounts that divide dry and humid climates. Notice that a station with an annual mean of 20°C (68°F) and a summer rainfall maximum of 68 centimeters (26.5 inches) is classified as dry. If the rain falls primarily in winter, however, the station must receive only 40 centimeters (15.6 inches) or more to be considered humid. If the precipitation is more evenly distributed, the figure defining the humid–dry boundary is between the other two.

TABLE 19.A Average Annual Precipitation Defining the Boundary between Dry and Humid Climates

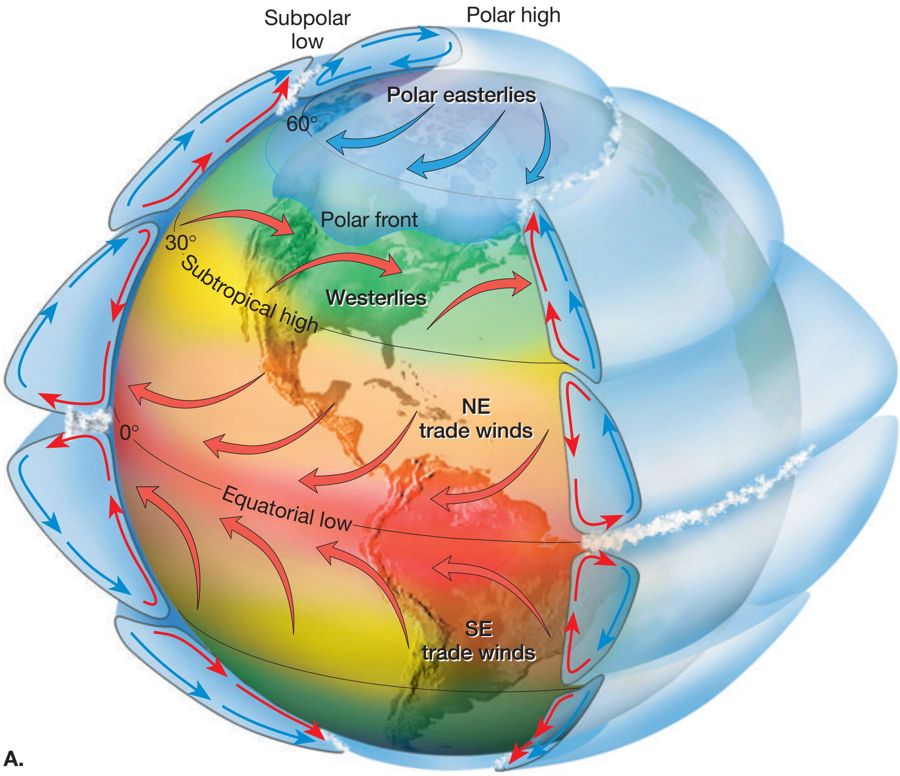
Average Rainfall Annual Temp. (C°)	Winter Rainfall Maximum (centimeters)	Even Distribution (centimeters)	Summer Maximum (centimeters)
5	10	24	38
10	20	34	48
15	30	44	58
20	40	54	68
25	50	64	78
30	60	74	88

In the Southern Hemisphere, dry climates dominate Australia. Almost 40 percent of the continent is desert, and much of the remainder is steppe. In addition, arid and semiarid areas occur in southern Africa and make a limited appearance in coastal Chile and Peru.

What causes these bands of low-latitude desert? The answer is the global distribution of air pressure and winds. Figure 19.3A, an idealized diagram of Earth's general circulation, helps visualize the relationship. Heated air in the pressure belt known as the *equatorial low* rises to great heights (usually between 15 and 20 kilometers) and then spreads out. As the upper-level flow reaches 20° to 30° latitude, north or south, it sinks toward the surface. Air that rises through the atmosphere expands and cools, a process that leads to the development of clouds and precipitation. For this reason, the areas under the influence of the equatorial low are among the rainiest on Earth. Just the opposite is true for the regions in the vicinity of 30° north and south latitude, where high pressure predominates. Here, in the zones known as the *subtropical highs,* air is subsiding. When air sinks, it is compressed and warmed. Such conditions are just opposite of what is needed to produce clouds and precipitation. Consequently, these regions are known for their clear skies, sunshine, and ongoing drought (Figure 19.3B).

Middle-Latitude Deserts

Unlike their low-latitude counterparts, middle-latitude deserts and steppes are not controlled by the subsiding air masses associated with high pressure. Instead, these dry lands exist principally because they are sheltered in the deep interiors of large landmasses. They are far removed



A.

B.

FIGURE 19.3 **A.** Idealized diagram of Earth's general circulation. The deserts and steppes that are centered in the latitude belt between 20° and 30° north and south coincide with the subtropical high-pressure belts. Here dry, subsiding air inhibits cloud formation and precipitation. By contrast, the pressure belt known as the equatorial low is associated with areas that are among the rainiest on Earth. **B.** In this view of Earth from space, North Africa's Sahara Desert, the adjacent Arabian Desert, and the Kalahari and Namib deserts in southern Africa are clearly visible as tan-colored, cloud-free zones. The band of clouds that extends across central Africa and the adjacent oceans coincides with the equatorial low-pressure belt. (Photo courtesy of NASA/Science Source/Photo Researchers, Inc.)

from the ocean, which is the ultimate source of moisture for cloud formation and precipitation. One well-known example is the Gobi Desert of central Asia, shown on the map north of India.

The presence of high mountains across the paths of prevailing winds further separates these areas from water-bearing, maritime air masses; plus, the mountains force the air to lose much of its water. The mechanism is simple: As prevailing winds meet mountain barriers, the air is forced to ascend. When air rises, it expands and cools, a process that can produce clouds and precipitation. The windward sides of mountains, therefore, often have high precipitation. By contrast, the leeward sides of mountains are usually much drier (Figure 19.4). This situation exists because air reaching the leeward side has lost much of its moisture, and if the air descends, it is compressed and warmed, making cloud formation even less likely. The dry region that results is often referred to as a **rainshadow desert.** Because many middle-latitude deserts occupy sites on the leeward sides of mountains, they can also be classified as rainshadow deserts. In North America, the foremost

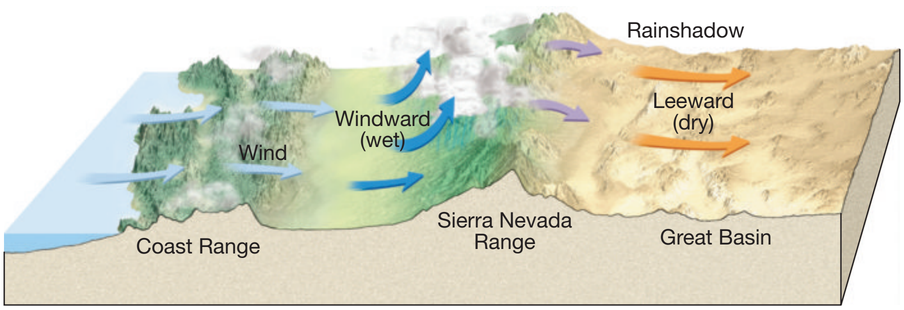


FIGURE 19.4 Many deserts in the middle latitudes are rainshadow deserts. As moving air meets a mountain barrier, it is forced to rise. Clouds and precipitation on the windward side often result. Air descending the leeward side is much drier. The mountains effectively cut the leeward side off from the sources of moisture, producing a rainshadow desert. The Great Basin desert is a rainshadow desert that covers nearly all of Nevada and portions of adjacent states.

Students Sometimes Ask . . .

Are all deserts hot?

No, but many deserts do experience some very high temperatures. For instance, the highest authentically recorded temperature in the United States—as well as the entire Western Hemisphere—is 57°C (134°F), measured at Death Valley, California, on July 10, 1913. The world-record high temperature of nearly 59°C (137°F) was recorded in Azizia, Libya, in North Africa's Sahara Desert on September 13, 1922.

Despite these remarkably high figures, cold temperatures are also experienced in desert regions. For example, the average daily minimum temperature in January in Phoenix, Arizona, is 1.7°C (35°F), just barely above freezing. At Ulan Bator in Mongolia's Gobi Desert the average *high* temperature on January days is only −19°C (−2°F). Dry climates are found from the tropics poleward to the high middle latitudes. Although tropical deserts lack a cold season, deserts in the middle latitudes do experience seasonal temperature changes, which cause some to get quite cold.

mountain barriers to moisture from the Pacific are the Coast Ranges, Sierra Nevada, and Cascades. (Figure 19.4). In Asia, the great Himalayan chain prevents the summertime monsoon flow of moist Indian Ocean air from reaching the interior (see Box 19.2).

Because the Southern Hemisphere lacks extensive land areas in the middle latitudes, only a small area of desert and steppe occurs in this latitude range, existing primarily near the southern tip of South America in the rainshadow of the towering Andes.

The middle-latitude deserts provide an example of how tectonic processes affect climate. Rainshadow deserts exist by virtue of the mountains produced when plates collide. Without such mountain-building episodes, wetter climates would prevail where many dry regions exist today.

Geologic Processes in Arid Climates

GEODe EARTH
Deserts and Winds
▸ **Common Misconceptions About Deserts**

The angular hills, the sheer canyon walls, and the desert surface of pebbles or sand contrast sharply with the rounded hills and curving slopes of more humid places. Indeed, to a visitor from a humid region, a desert landscape may seem to have been shaped by forces different from those operating in well-watered areas. However, although the contrasts may be striking, they do not reflect different processes. They merely disclose the differing effects of the same processes that operate under contrasting climatic conditions.

Weathering

In humid regions, relatively fine-textured soils support an almost continuous cover of vegetation that mantles the surface. Here the slopes and rock edges are rounded, reflecting the strong influence of chemical weathering in a humid climate. By contrast, much of the weathered debris in deserts consists of unaltered rock and mineral fragments—the result of mechanical weathering processes. In dry lands, rock weathering of any type is greatly reduced because of the lack of moisture and the scarcity of organic acids from decaying plants. However, chemical weathering is not completely lacking in deserts. Over long spans of time, clays and thin soils do form, and many iron-bearing silicate minerals oxidize, producing the rust-colored stain that tints some desert landscapes.

The Role of Water

Permanent streams are normal in humid regions, but practically all desert streambeds are dry most of the time (Figure 19.5A). Deserts have **ephemeral** (*ephemero* = short-lived) **streams,** which means they carry water only in response to specific episodes of rainfall. A typical ephemeral stream might flow only a few days or perhaps just a few hours during the year. In some years the channel might carry no water at all.

This fact is obvious even to the casual traveler who notices numerous bridges with no streams beneath them or numerous dips in the road where dry channels cross. However, when the rare heavy showers do come, so much rain falls in such a short time that all of it cannot soak in (Figure 19.6). Because desert vegetative cover is sparse, runoff is largely unhindered and consequently rapid, often creating flash floods along valley floors (Figure 19.5B). These floods are quite unlike floods in humid regions. A flood on a river like the Mississippi may take several days to reach its crest and then subside. But desert floods arrive suddenly and subside quickly. Because much surface material in a desert is not anchored by vegetation, the amount of erosional work that occurs during a single short-lived rain event is impressive.

In the dry western United States, different names are used for ephemeral streams, including *wash* and *arroyo*. In other parts of the world, a dry desert stream may be a *wadi* (Arabia and North Africa), a *donga* (South America), or a *nullah* (India).

Humid regions are notable for their integrated drainage systems. But in arid regions, streams usually lack an extensive system of tributaries. In fact, a basic characteristic of desert streams is that they are small and die out before reaching the sea. Because the water table is usually far below the surface, few desert streams can draw upon it as streams do in humid regions (see Figure 17.4, p. 461). Without a steady supply of water, the combination of evaporation and infiltration soon depletes the stream.

The few permanent streams that do cross arid regions, such as the Colorado and Nile rivers, originate *outside* the desert, often in well-watered mountains. Here the water supply must be great to compensate for the losses occurring as the stream crosses the desert. For example, after the Nile

BOX 19.2 ▶ PEOPLE AND THE ENVIRONMENT

The Disappearing Aral Sea

The Aral Sea lies on the border between Uzbekistan and Kazakhstan in central Asia (Figure 19.A). The setting is the Turkestan desert, a middle-latitude desert in the rainshadow of Afghanistan's high mountains. In this region of interior drainage, two large rivers, the Amu Darya and the Syr Darya, carry water from the mountains of northern Afghanistan across the desert to the Aral Sea. Water leaves the sea by evaporation. Thus, the size of the water body depends upon the balance between river inflow and evaporation.

In 1960 the Aral Sea was one of the world's largest inland water bodies, with an area of about 67,000 square kilometers (26,000 square miles). Only the Caspian Sea, Lake Superior, and Lake Victoria were larger. By the year 2000 the sea had shrunk by 75 percent and split into 2 parts joined by a narrow passage. The water level had dropped 22 meters (72 feet) and the sea had lost 90 percent of its volume. The shrinking of this water body is depicted in Figure 19.B. By about 2010 all that will likely remain will be three shallow remnants.

What caused the Aral Sea to dry up over the past 40 years? The answer is that the flow of water from the mountains that supplied the sea was significantly reduced and then all but eliminated. As recently as 1965, the Aral Sea received about 50 cubic kilometers (12 cubic miles) of fresh water per year. By the early 1980s this number fell to nearly zero. The reason was that the waters of the Amu Darya and Syr Darya were diverted to supply a major expansion of irrigated agriculture in this dry realm.

The intensive irrigation greatly increased agricultural productivity, but not without significant costs. The deltas of the two major rivers have lost their wetlands, and wildlife has disappeared. The once thriving fishing industry is dead, and the 24 species of fish that once lived in the Aral Sea are no longer there. The shoreline is now tens of kilometers from the towns that were once fishing centers (Figure 19.C).

The shrinking sea has exposed millions of acres of former seabed to sun and wind. The surface is encrusted with salt and with agrochemicals brought by the rivers. Strong winds routinely pick up and deposit thousands of tons of newly exposed material every year. This process has not only contributed to a significant reduction in air quality for people living in the region but has also appreciably affected crop yields due to the deposition of salt-rich sediments on arable land.

The shrinking Aral Sea has had a noticeable impact on the region's climate. Without the moderating effect of a large water body, there are greater extremes of temperature, a shorter growing season, and reduced local precipitation. These changes have caused many farms to switch from growing cotton to growing rice, which demands even more diverted water.

Environmental experts agree that the current situation cannot be sustained. Could this crisis be reversed if enough fresh water were to once again flow into the Aral Sea?

Prospects appear grim. Experts estimate that restoring the Aral Sea to about twice its present size would require stopping all irrigation from the two major rivers for 50 years. This could not be done without ruining the economies of the countries that rely on that water.*

The decline of the Aral Sea is a major environmental disaster that sadly is of human making.

*For more on this, see "Coming to Grips with the Aral Sea's Grim Legacy," in *Science*, vol. 284, April 2, 1999, pp. 30–31. and "To Save a Vanishing Sea" in *Science* vol. 307, February 18, 2005, pp. 1032–33.

FIGURE 19.A The Aral Sea lies east of the Caspian Sea in the Turkestan Desert. Two rivers, the Amu Darya and Syr Darya, bring water from the mountains to the south.

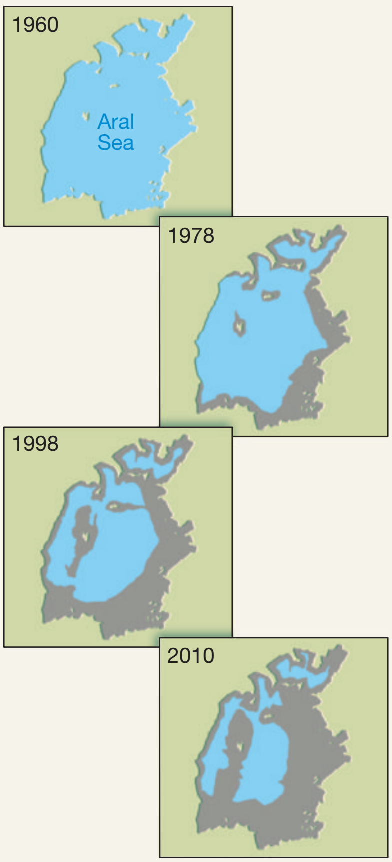


FIGURE 19.B The shrinking Aral Sea. By the year 2010 all that will remain are three small remnants.

FIGURE 19.C In the town of Jamboul, Kazakhstan, boats now lie in the sand because the Aral Sea has dried up. (Photo by Ergun Cagatay/Liaison Agency, Inc.)

A. B.

FIGURE 19.5 **A.** Most of the time, desert stream channels are dry. **B.** An ephemeral stream shortly after a heavy shower. Although such floods are short-lived, large amounts of erosion occur. (Photos by E. J. Tarbuck)

leaves its headwaters in the lakes and mountains of central Africa, it traverses almost 3000 kilometers of the Sahara without a single tributary. By contrast, in humid regions the discharge of a river grows as it flows downstream because tributaries and groundwater contribute additional water along the way.

FIGURE 19.6 Desert thunderstorm over Tucson, Arizona. There are often many weeks, months, or occasionally even years separating periods of rain in the desert. When rains do occur, they are often heavy and of relatively short duration. Because the rainfall intensity is high, all of the water cannot soak in, and rapid runoff results. (Photo by Warren Faidley/DRK Photo)

It should be emphasized that *running water, although infrequent, nevertheless does most of the erosional work in deserts.* This is contrary to the common belief that wind is the most important erosional agent sculpturing desert landscapes. Although wind erosion is indeed more significant in dry areas than elsewhere, most desert landforms are carved by running water. As you will see shortly, the main role of wind is in the transportation and deposition of sediment, which creates and shapes the ridges and mounds we call dunes.

Basin and Range: The Evolution of a Desert Landscape

GEODe EARTH **Deserts and Winds**
▸ **Reviewing Landforms and Landscapes**

Because arid regions typically lack permanent streams, they are characterized as having **interior drainage.** This means that they have a discontinuous pattern of intermittent streams that do not flow out of the desert to the ocean. In the United States, the dry Basin and Range region provides an excellent example. The region includes southern Oregon, all of Nevada, western Utah, southeastern California, southern Arizona, and southern New Mexico. The name Basin and Range is an apt description for this almost 800,000-square-kilometer region because it is characterized by more than 200 relatively small mountain ranges that rise 900 to 1500 meters (3000 to 5000 feet) above the basins that separate them.

In this region, as in others like it around the world, erosion mostly occurs without reference to the ocean (ultimate base level) because the interior drainage never reaches the sea.

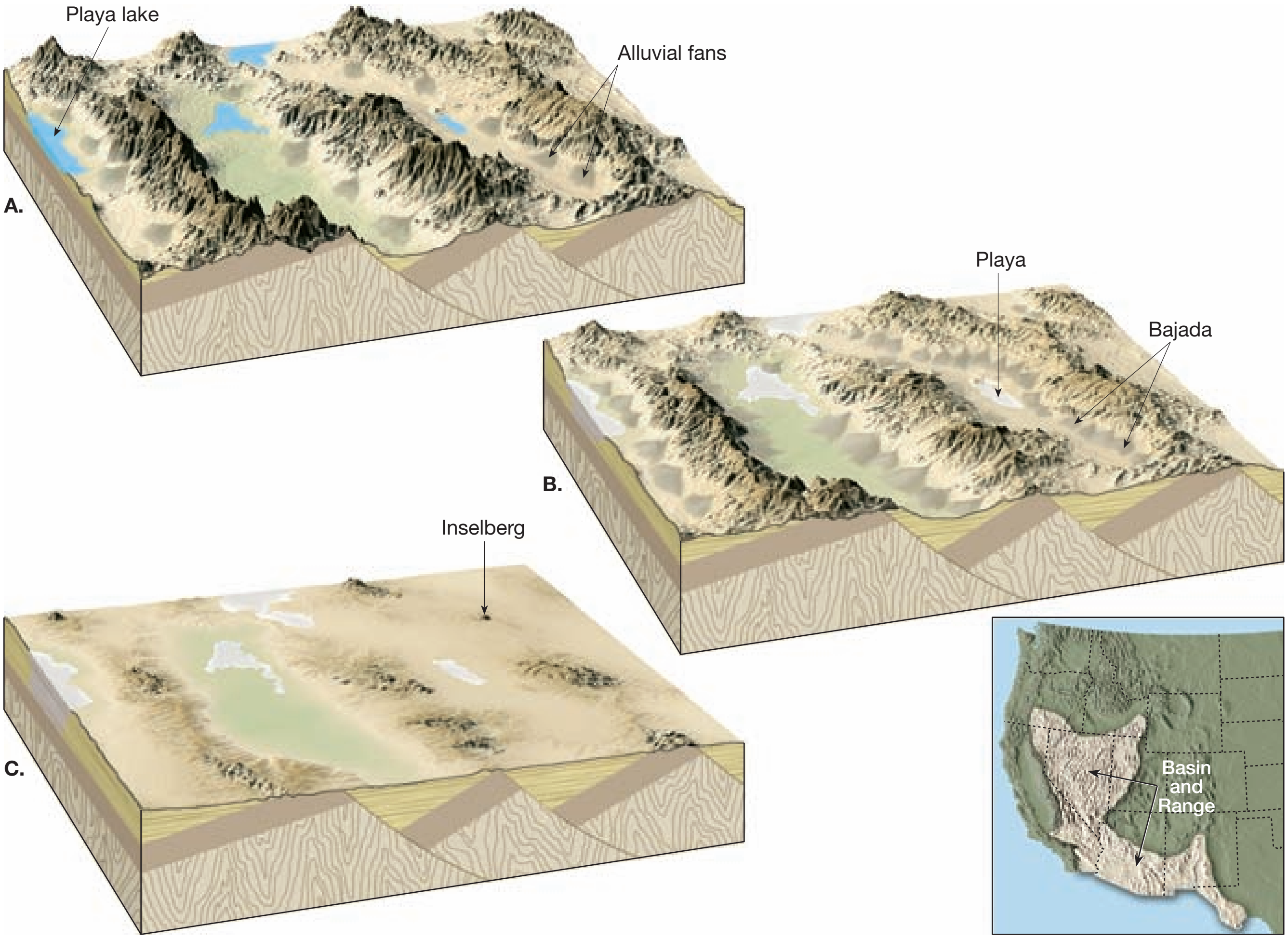


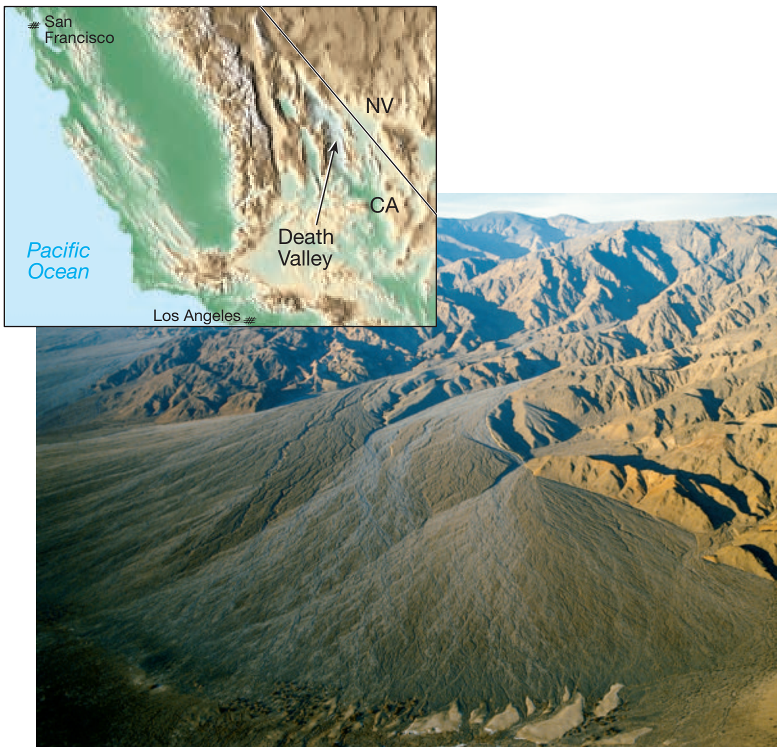
FIGURE 19.7 Stages of landscape evolution in a mountainous desert such as the Basin and Range region of the West. As erosion of the mountains and deposition in the basins continue, relief diminishes. **A.** Early stage. **B.** Middle stage. **C.** Late stage.

Even where permanent streams flow to the ocean, few tributaries exist, and thus only a narrow strip of land adjacent to the stream has sea level as its ultimate level of land reduction.

The block models in Figure 19.7 depict how the landscape has evolved in the Basin and Range region. During and following the uplift of the mountains, running water begins carving the elevated mass and depositing large quantities of debris in the basin. During this early stage, relief is greatest, because as erosion lowers the mountains and sediment fills the basins, elevation differences gradually diminish.

When the occasional torrents of water produced by sporadic rains move down the mountain canyons, they are heavily loaded with sediment. Emerging from the confines of the canyon, the runoff spreads over the gentler slopes at the base of the mountains and quickly loses velocity. Consequently, most of its load is dumped within a short distance. The result is a cone of debris at the mouth of a canyon known as an alluvial fan (Figure 19.8). Because the coarsest material is dropped first, the head of the fan is steepest, having a slope of perhaps 10 to 15 degrees. Moving down the fan, the size of the sediment and the steepness of the slope decrease and merge imperceptibly with the basin

FIGURE 19.8 Aerial view of alluvial fans in Death Valley, California. The size of the fan depends on the size of the drainage basin. As the fans grow, they eventually coalesce to form a bajada. (Photo by Michael Collier)



BOX 19.3 ▶ UNDERSTANDING EARTH

Australia's Mount Uluru

When travelers contemplating a trip to Australia consult brochures and other tourist literature, they are bound to see a photograph or read a description of Mount Uluru (formerly Ayers Rock). As Figure 19.D illustrates, this well-known attraction is a massive feature that rises steeply from the surrounding plain. Located in Uluru–Kata Tjuta National Park, southwest of Alice Springs in the dry center of the continent, the roughly circular monolith is more than 350 meters (1200 feet) high, and its base is more than 9.5 kilometers (6 miles) in circumference. Its summit is flattened, its sides furrowed. The rock type is sandstone, and the hues of red and orange change with the light of day. In addition to being a striking geological attraction, Mount Uluru is of interest because it is a sacred place for the aboriginal tribes of the region.

FIGURE 19.D Mount Uluru (formerly Ayers Rock) rises conspicuously above the dry plains of central Australia. It is a type of inselberg known as a *bornhardt.* As erosion gradually lowers the surface, the less weathered massive rock remains standing high above the more jointed and more easily weathered rock that surrounds it. (Photo by Art Wolfe, Inc.)

Mount Uluru is a spectacular example of a feature known as an inselberg. *Inselberg* is a German word meaning "island mountain" and seems appropriate because these masses clearly resemble rocky islands standing above the surface of a broad sea. Similar features are scattered throughout many other arid and semiarid regions of the world. Mount Uluru is a special type of inselberg that consists of a very resistant rock mass exhibiting a rounded or domed form. Such masses are termed *bornhardts* for the 19th-century German explorer Wilhelm Bornhardt, who described similar features in parts of Africa.

Bornhardts form in regions where massive or resistant rock such as granite or sandstone is surrounded by rock that is more susceptible to weathering. The greater susceptibility of the adjacent rock is often the result of its being more highly jointed. Joints allow water and therefore weathering processes to penetrate to greater depths. When the adjacent, deeply weathered rock is stripped away by erosion, the far less weathered rock mass remains standing high. After a bornhardt forms, it tends to shed water. By contrast, the surrounding a bornhardt helps to perpetuate its existence by reinforcing the processes that created it. In fact, masses such as Mount Uluru can remain a part of the landscape for tens of millions of years.

Bornhardts are more common in the lower latitudes because the weathering that is responsible for their formation proceeds more rapidly in warmer climates. In regions that are now arid or semiarid, bornhardts may reflect times when the climate was wetter than it is today.

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floor. An examination of the fan's surface would likely reveal a braided channel pattern because of the water shifting its course as successive channels became choked with sediment. Over the years a fan enlarges, eventually coalescing with fans from adjacent canyons to produce an apron of sediment called a **bajada** along the mountain front.

On the rare occasions of abundant rainfall, streams may flow across the bajada to the center of the basin, converting the basin floor into a shallow **playa lake.** Playa lakes are temporary features that last only a few days or at best a few weeks before evaporation and infiltration remove the water. The dry, flat lake bed that remains is called a **playa.** Playas are typically composed of fine silts and clays and are occasionally encrusted with salts precipitated during evaporation (see Figure 7.15, p. 205). These precipitated salts may be unusual. A case in point is the sodium borate (better known as borax) mined from ancient playa lake deposits in Death Valley, California.

With the ongoing erosion of the mountain mass and the accompanying sedimentation, the local relief continues to diminish. Eventually nearly the entire mountain mass is gone. Thus, by the late stages of erosion, the mountain areas are reduced to a few large bedrock knobs projecting above the surrounding sediment-filled basin. These isolated erosional remnants on a late-stage desert landscape are called **inselbergs,** a German word meaning "island mountains" (see Box 19.3).

Each of the stages of landscape evolution in an arid climate depicted in Figure 19.7 can be observed in the Basin and Range region. Recently uplifted mountains in an early stage of erosion are found in southern Oregon and northern Nevada. Death Valley, California, and southern Nevada fit

Students Sometimes Ask . . .

Where is the driest desert on Earth?

The Atacama Desert of Chile has the distinction of being the world's driest desert. This relatively narrow belt of arid land extends for about 1200 kilometers (750 miles) along South America's Pacific Coast (see Figure 19.2). It is said that some portions of the Atacama have not received rain for more than 400 years! One must view such pronouncements skeptically. Nevertheless, for places where records have been kept, Arica, Chile, in the northern part of the Atacama, has experienced a span of 14 years without measurable rainfall.

into the more advanced middle stage, whereas the late stage, with its inselbergs, can be seen in southern Arizona.

Transportation of Sediment by Wind

Moving air, like moving water, is turbulent and able to pick up loose debris and transport it to other locations. Just as in a stream, the velocity of wind increases with height above the surface. Also like a stream, wind transports fine particles in suspension while heavier ones are carried as bed load. However, the transport of sediment by wind differs from that of running water in two significant ways. First, wind's lower density compared to water renders it less capable of picking up and transporting coarse materials. Second, because wind is not confined to channels, it can spread sediment over large areas, as well as high into the atmosphere.

Bed Load

The **bed load** carried by wind consists of sand grains. Observations in the field and experiments using wind tunnels indicate that windblown sand moves by skipping and bouncing along the surface—a process termed **saltation.** The term is not a reference to salt, but instead derives from the Latin word meaning "to jump."

The movement of sand grains begins when wind reaches a velocity sufficient to overcome the inertia of the resting particles. At first the sand rolls along the surface. When a moving sand grain strikes another grain, one or both of them may jump into the air. Once in the air, the grains are carried forward by the wind until gravity pulls them back toward the surface. When the sand hits the surface, it either bounces back into the air or dislodges other grains, which then jump upward. In this manner, a chain reaction is established, filling the air near the ground with saltating sand grains in a short period of time (Figure 19.9).

Bouncing sand grains never travel far from the surface. Even when winds are very strong, the height of the saltating sand seldom exceeds a meter and usually is no greater than a half meter. Some sand grains are too large to be thrown into the air by impact from other particles. When this is the case, the energy provided by the impact of the smaller saltating grains drives the larger grains forward. Estimates indicate that between 20 and 25 percent of the sand transported in a sandstorm is moved in this way.

Suspended Load

Unlike sand, finer particles of dust can be swept high into the atmosphere by the wind. Because dust is often composed of rather flat particles that have large surface areas compared to their weight, it is relatively easy for turbulent air to counterbalance the pull of gravity and keep these fine particles airborne for hours or even days. Although both silt and clay can be carried in suspension, silt commonly makes up the bulk of the **suspended load** because the reduced level of chemical weathering in deserts provides only small amounts of clay.

Fine particles are easily carried by the wind, but they are not so easily picked up to begin with. The reason is that the wind velocity is practically zero within a very thin layer close to the ground. Thus, the wind cannot lift the sediment by itself. Instead, the dust must be ejected or spattered into the moving air by bouncing sand grains or other disturbances. This idea is illustrated nicely by a dry, unpaved country road on a windy day. Left undisturbed, little dust is raised by the wind. However, as a car or truck moves over the road, the layer of silt is kicked up, creating a thick cloud of dust.

Although the suspended load is usually deposited relatively near its source, high winds are capable of carrying large quantities of dust great distances (Figure 19.10). In the 1930s, silt that was picked up in Kansas was transported to New England and beyond into the North Atlantic. Similarly, dust blown from the Sahara has been traced as far as the West Indies (Figure 19.11).

FIGURE 19.9 A cloud of saltating sand grains moving up the gentle slope of a dune. (Photo by Stephen Trimble)

FIGURE 19.10 Dust blackens the sky on May 21, 1937, near Elkhart, Kansas. It was because of storms like this that portions of the Great Plains were called the "Dust Bowl" in the 1930s. (Photo reproduced from the collection of the Library of Congress)

Wind Erosion

Deserts and Winds
▸ Common Misconceptions About Deserts

Compared to running water and glaciers, wind is a relatively insignificant erosional agent. Recall that even in deserts, most erosion is performed by intermittent running water, not by the wind. Wind erosion is more effective in arid lands than in humid areas because in humid places moisture binds particles together and vegetation anchors the soil. For wind to be an effective erosional force, dryness and scanty vegetation are important prerequisites (see Box 19.4). When such circumstances exist, wind may pick up, transport, and deposit great quantities of fine sediment. During the 1930s, parts of the Great Plains experienced vast dust storms. The plowing under of the natural vegetative cover for farming, followed by severe drought, exposed the land to wind erosion and led to the area's being labeled the Dust Bowl.*

FIGURE 19.11 This satellite image shows thick plumes of dust from the Sahara Desert blowing across the Mediterranean Sea toward Italy on July 16, 2003. Such dust storms are common in arid North Africa. In fact, this region is the largest dust source in the world. Satellites are an excellent tool for studying the transport of dust on a global scale. They show that dust storms can cover huge areas and that dust can be transported great distances. (Image courtesy of NASA)

Deflation and Blowouts

One way that wind erodes is by **deflation** (*de* = out, *flat* = blow),the lifting and removal of loose material. Deflation sometimes is difficult to notice because the entire surface is being lowered at the same time, but it can be significant. In portions of the 1930s Dust Bowl, vast areas of land were lowered by as much as a meter in only a few years.

The most noticeable results of deflation in some places are shallow depressions appropriately called **blowouts** (Figure 19.12). In the Great Plains region, from Texas north to Montana, thousands of blowouts are visible on the landscape. They range from small dimples less than a meter deep and 3 meters wide to depressions that approach 50 meters in depth and several kilometers across. The factor that controls the depths of these basins (that is, acts as base level) is the local water table. When blowouts are lowered to the water table, damp ground and vegetation prevent further deflation.

Desert Pavement

In portions of many deserts, the surface consists of a closely packed layer of coarse particles. This veneer of pebbles and cobbles, called **desert pavement,** is only one or two stones thick (Figure 19.13). Beneath is a layer containing a significant proportion of silt and sand. When desert pavement is present, it is an important control on wind erosion because pavement stones are too large for deflation to remove. When this armor is disturbed, wind can easily erode the exposed fine silt.

For many years, the most common explanation for the formation of desert pavement was that it develops when wind removes sand and silt within poorly sorted surface deposits. As Figure 19.14A illustrates, the concentration of larger particles at the surface gradually increases as the finer particles are blown away. Eventually the surface is completely covered with pebbles and cobbles too large to be moved by the wind.

Studies have shown that the process depicted in Figure 19.14A is not an adequate explanation for all environments in which desert pavement exists. For example, in many places, desert pavement is underlain by a relatively thick layer of silt that contains few if any pebbles and cobbles. In such a setting, deflation of fine sediment could not leave behind a layer of coarse particles. Studies also showed that in some areas the pebbles and cobbles composing desert pavement have all been exposed at the surface for about the same length of time. This would not be the case for the process shown in Figure 19.14A. Here, the coarse particles that make up the pavement reach the surface over an extended time span as deflation gradually removes the fine material.

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*For more information, see Box 6.4 (p. 188), "Dust Bowl—Soil Erosion in the Great Plains."

BOX 19.4 ▶ PEOPLE AND THE ENVIRONMENT

Deserts Are Expanding

The transition zones surrounding deserts have very fragile, delicately balanced ecosystems. In these marginal areas, human activities may stress the ecosystem beyond its tolerance limit, resulting in degradation of the land. If such degradation is severe, it is referred to as *desertification*. Desertification means the expansion of desertlike conditions into nondesert areas. Although such a transformation can also result from natural processes that act over decades, centuries, or even millennia, in recent years, desertification has come to mean the rapid alteration of land to desertlike conditions as the result of human activities.

The United Nations has recognized desertification as one of the most serious environmental challenges of the 21st century. According to the U.N.'s International Fund for Agricultural Development, each year desertification claims another 10 million acres of agricultural drylands. In response, more than 190 countries (including the United States) have ratified a treaty known as the Convention to Combat Desertification.

The advancement of desertlike conditions into areas that were previously useful for agriculture is not a uniform, clear-cut shifting of desert borders. Rather, degeneration into desert usually occurs as a patchy transformation of dry but habitable land into dry, uninhabitable land. It results primarily from inappropriate land use and is aided and accelerated by drought. Unfortunately, an area undergoing desertification comes to our attention only after the process is well under way.

Desertification begins when land near the desert's edge is used for growing crops or for grazing livestock. Either way, the natural vegetation is removed by plowing or grazing.

If crops are planted and drought occurs, the unprotected soil is exposed to the forces of erosion. Gullying of slopes and accumulations of sediment in stream channels are visible signs on the landscape, as are the clouds of dust created as topsoil is removed by the wind.

Where livestock are raised, the land is also degraded. Although the modest natural vegetation on marginal lands can maintain local wildlife, it cannot support the intensive grazing of large domesticated herds. Overgrazing reduces or eliminates plant cover. When the vegetative cover is destroyed beyond the minimum required to hold the soil against erosion, the destruction becomes irreversible. Moreover, by pounding the ground with their hooves, livestock compact the soil, which reduces the amount of water the land can soak up when it does rain. The pounding hooves also pulverize the soil, increasing the proportion of fine material, which is then more easily removed when winds are strong.

Desertification first received worldwide attention when drought struck a region in Africa called the *Sahel* in the late 1960s (Figure 19.E). During that period, and many subsequent episodes, the people in this vast expanse south of the Sahara Desert have suffered malnutrition and death by starvation. Livestock herds have been decimated, and the loss of productive land has been great (Figure 19.F). Hundreds of thousands of people have been forced to migrate. As agricultural lands shrink, people must rely on smaller areas for food production. This, in turn, stresses the environment and accelerates the desertification process.

Although human suffering from desertification is most serious in the Sahel, the problem is by no means confined to that region. Desertification exists in other parts of Africa and on every other continent except Antarctica. Recurrent droughts may seem to be the obvious reason for desertification, but the chief cause is stress placed by people on a tenuous environment with fragile soils.

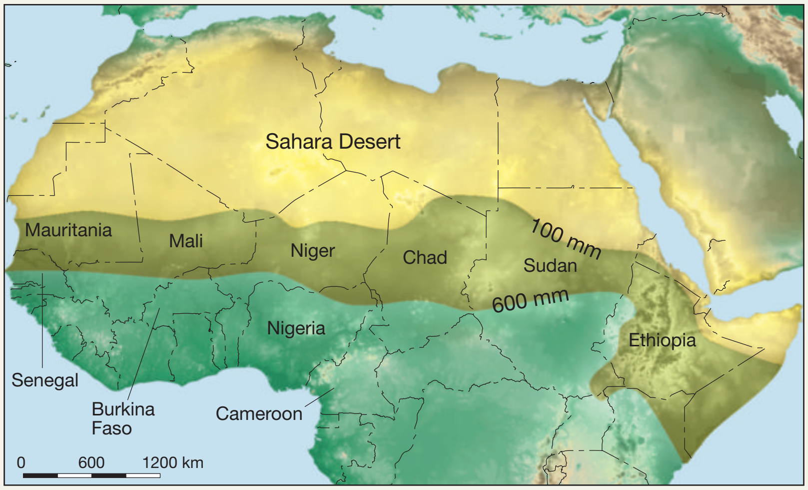
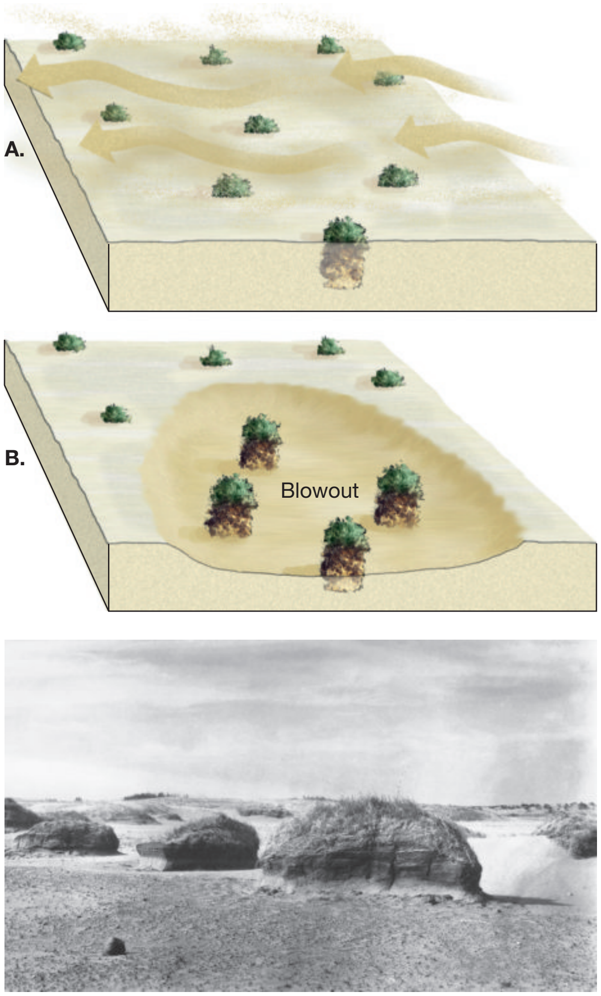


FIGURE 19.E Desertification is most serious in the southern margin of the Sahara in a region known as the Sahel. The lines defining the approximate boundaries of the Sahel represent average annual rainfall in millimeters.

FIGURE 19.F Overgrazing of marginal lands in Africa south of the Sahara has contributed to desertification. (Photo by Sean Sprague/Peter Arnold, Inc.)



C.

FIGURE 19.12 Formation of a blowout. **A.** Area prior to deflation. **B.** Area after deflation has created a shallow depression. **C.** This photo was taken north of Granville, North Dakota, in July 1936, during a prolonged drought. Strong winds removed the soil that was not anchored by vegetation. The mounds are 1.2 meters (4 feet) high and show the level of the land prior to deflation. (Photo courtesy of the State Historical Society of North Dakota, col 278-1)

As a result, an alternate explanation for desert pavement was formulated (Figure 19.14B). This hypothesis suggests that pavement develops on a surface that initially consists of coarse particles. Over time, protruding cobbles trap fine, windblown grains that settle and sift downward through the spaces between the larger surface stones. The process is aided by infiltrating rainwater. In this model, the cobbles composing the pavement were never buried. Moreover, it successfully explains the lack of coarse particles beneath the desert pavement.

Ventifacts and Yardangs

Like glaciers and streams, wind also erodes by **abrasion** (*ab* = away, *radere* = to scrape). In dry regions as well as along some beaches, windblown sand cuts and polishes exposed rock surfaces. Abrasion sometimes creates interestingly shaped stones called **ventifacts** (Figure 19.15A). The side of the stone exposed to the prevailing wind is abraded, leaving it polished, pitted, and with sharp edges. If the wind is not consistently from one direction, or if the pebble becomes reoriented, it may have several faceted surfaces.

Unfortunately, abrasion is often given credit for accomplishments beyond its capabilities. Such features as balanced rocks that stand high atop narrow pedestals, and intricate detailing on tall pinnacles, are not the results of abrasion. Sand seldom travels more than a meter above the surface, so the wind's sandblasting effect is obviously limited in vertical extent.

In addition to ventifacts, wind erosion is responsible for creating much larger features, called yardangs (from the Turkistani word *yar,* meaning "steep bank"). A **yardang** is a streamlined, wind-sculpted landform that is oriented parallel to the prevailing wind (Figure 19.15B). Individual yardangs are generally small features that stand less than 5 meters (16 feet) high and no more than about 10 meters (32 feet) long. Because the sandblasting effect of wind is greatest near the ground, these abraded bedrock remnants are usually narrower at their base. Sometimes yardangs are large features. Peru's Ica Valley contains yardangs that approach 100 meters (330 feet) in height and several kilometers in length. Some in the desert of Iran reach 150 meters (nearly 500 feet) in height.

Wind Deposits

GEODe EARTH **Deserts and Winds**
▸ **Reviewing Landforms and Landscapes**

Although wind is relatively unimportant in producing *erosional* landforms, significant *depositional* landforms are created by the wind in some regions. Accumulations of windblown sediment are particularly conspicuous in the world's dry lands and along many sandy coasts. Wind deposits are of two distinctive types: (1) mounds and ridges of sand from the wind's bed load, which we call dunes, and (2) extensive blankets of silt, called loess, that once were carried in suspension.

FIGURE 19.13 Desert pavement consists of a closely packed veneer of pebbles and cobbles that is only one or two stones thick. Beneath the pavement is material containing a significant proportion of finer particles. If left undisturbed, desert pavement will protect the surface from deflation. (Photo by Bobbé Christopherson)

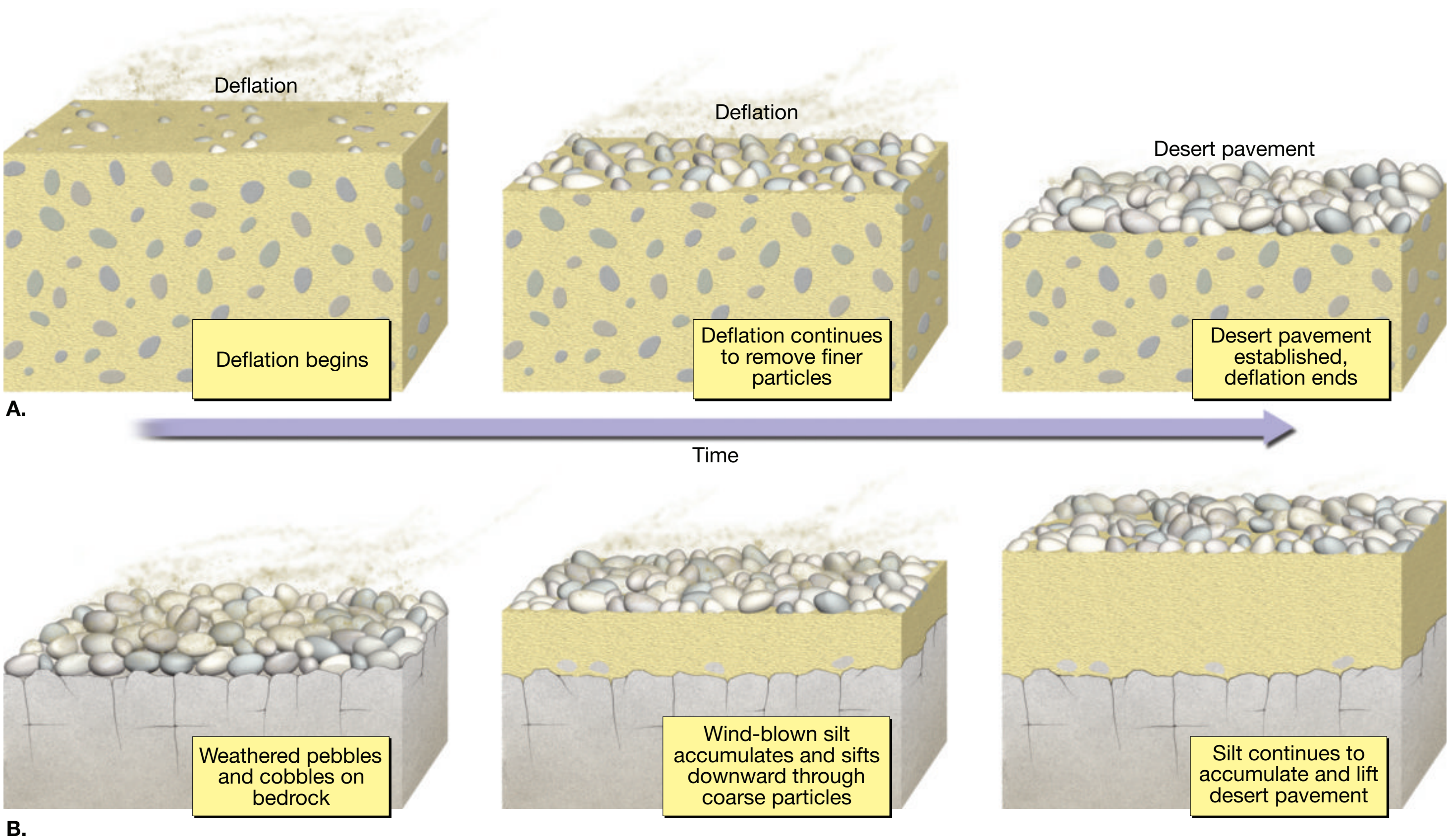


FIGURE 19.14 **A.** This model portrays an area with poorly sorted surface deposits. Coarse particles gradually become concentrated into a tightly packed layer as deflation lowers the surface by removing sand and silt. Here desert pavement is the result of wind erosion. **B.** This model shows the formation of desert pavement on a surface initially covered with coarse pebbles and cobbles. Windblown dust accumulates at the surface and gradually sifts downward through spaces between coarse particles. Infiltrating rainwater aids the process. This depositional process raises the surface and produces a layer of coarse pebbles and cobbles underlain by a substantial layer of fine sediment.

Sand Deposits

As is the case with running water, wind drops its load of sediment when velocity falls and the energy available for transport diminishes. Thus, sand begins to accumulate wherever an obstruction across the path of the wind slows its movement. Unlike many deposits of silt, which form blanketlike layers over large areas, winds commonly deposit sand in mounds or ridges called **dunes** (Figure 19.16).

As moving air encounters an object, such as a clump of vegetation or a rock, the wind sweeps around and over it, leaving a shadow of slower-moving air behind the obstacle, as well as a smaller zone of quieter air just in front of the obstacle. Some of the saltating sand grains moving with the wind come to rest

FIGURE 19.15 **A.** Ventifacts are rocks that are polished and shaped by sandblasting (Photo by Stephen Trimble). **B.** Yardangs are usually small, wind-sculpted landforms that are aligned parallel with the wind. (Photo by David Love, New Mexico Bureau of Geology and Mineral Resources)

A.

B.

FIGURE 19.16 Sand sliding down the steep slipface of a dune, in White Sands National Monument, New Mexico. (Photo by Michael Collier)

in these wind shadows. As the accumulation of sand continues, it becomes a more imposing barrier to the wind and thus a more efficient trap for even more sand. If there is a sufficient supply of sand and the wind blows steadily for a long enough time, the mound of sand grows into a dune.

Many dunes have an asymmetrical profile, with the leeward (sheltered) slope being steep and the windward slope more gently inclined (Figure 19.17). Sand moves up the gentler slope on the windward side by saltation. Just beyond the crest of the dune, where the wind velocity is reduced, the sand accumulates. As more sand collects, the slope steepens and eventually some of it slides under the pull of gravity (Figure 19.16). In this way, the leeward slope of the dune, called the **slipface,** maintains an angle of about 34 degrees, the angle of repose for loose dry sand. (Recall from Chapter 15 that the angle of repose is the steepest angle at which loose material remains stable.) Continued sand accumulation, coupled with periodic slides down the slipface, results in the slow migration of the dune in the direction of air movement.

As sand is deposited on the slipface, layers form that are inclined in the direction the wind is blowing. These sloping layers are called **cross beds** (Figure 19.17). When the dunes are eventually buried under other layers of sediment and become part of the sedimentary rock record, their asymmetrical shape is destroyed, but the cross beds remain as testimony to their origin. Nowhere is cross-bedding more prominent than in the sandstone walls of Zion Canyon in southern Utah (Figure 19.17).

For some areas, moving sand is troublesome. In Figure 19.18 dunes are advancing across irrigated fields in Egypt. In portions of the Middle East, valuable oil rigs must be protected from encroaching dunes. In some cases, fences are built sufficiently upwind of the dunes to stop their migration. As sand continues to collect, however, the fences must be built higher. In Kuwait protective fences extend for almost 10 kilometers around one important oil field. Migrating dunes can also pose a problem to the construction and maintenance of highways and railroads that cross sandy desert regions. For example, to keep a portion of Highway 95 near Winnemucca, Nevada, open to traffic, sand must be taken away about three times a year. Each time, between 1500 and 4000 cubic meters of sand are removed. Attempts at stabilizing the dunes by planting different varieties of grasses have been unsuccessful because the meager rainfall cannot support the plants.

Types of Sand Dunes

Dunes are not just random heaps of windblown sediment. Rather, they are accumulations that usually assume patterns that are surprisingly consistent (Figure 19.18). Addressing this point, a leading early investigator of dunes, the British engineer R. A. Bagnold, observed: "Instead of finding chaos and disorder, the observer never fails to be amazed at a

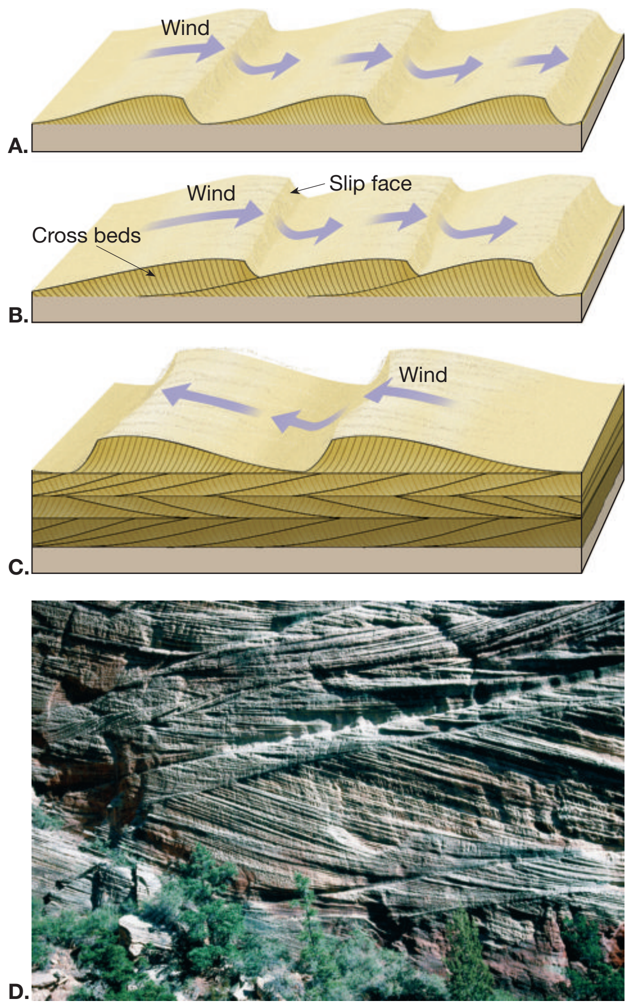


FIGURE 19.17 As parts **A** and **B** illustrate, dunes commonly have an asymmetrical shape. The steeper leeward side is called the *slipface.* Sand grains deposited on the slipface at the angle of repose create the cross-bedding of the dunes. **C.** A complex pattern develops in response to changes in wind direction. Also notice that when dunes are buried and become part of the sedimentary record, the cross-bedded structure is preserved. **D.** Cross beds are an obvious characteristic of the Navajo Sandstone in Zion National Park, Utah. (Photo by Marli Miller)

FIGURE 19.18 These desert dunes (called *barchans*) in Egypt are advancing from right to left across irrigated fields. (Photo by Georg Gerster/Photo Researchers, Inc.)

simplicity of form, an exactitude of repetition, and a geometric order. . . ." A broad assortment of dune forms exists, generally simplified to a few major types for discussion.

Of course, gradations exist among different forms as well as irregularly shaped dunes that do not fit easily into any category. Several factors influence the form and size that dunes ultimately assume. These include wind direction and velocity, availability of sand, and the amount of vegetation present. Six basic dune types are shown in Figure 19.19, with arrows indicating wind directions.

Barchan Dunes Solitary sand dunes shaped like crescents and with their tips pointing downwind are called **barchan dunes** (Figures 19.18 and 19.19A). These dunes form where

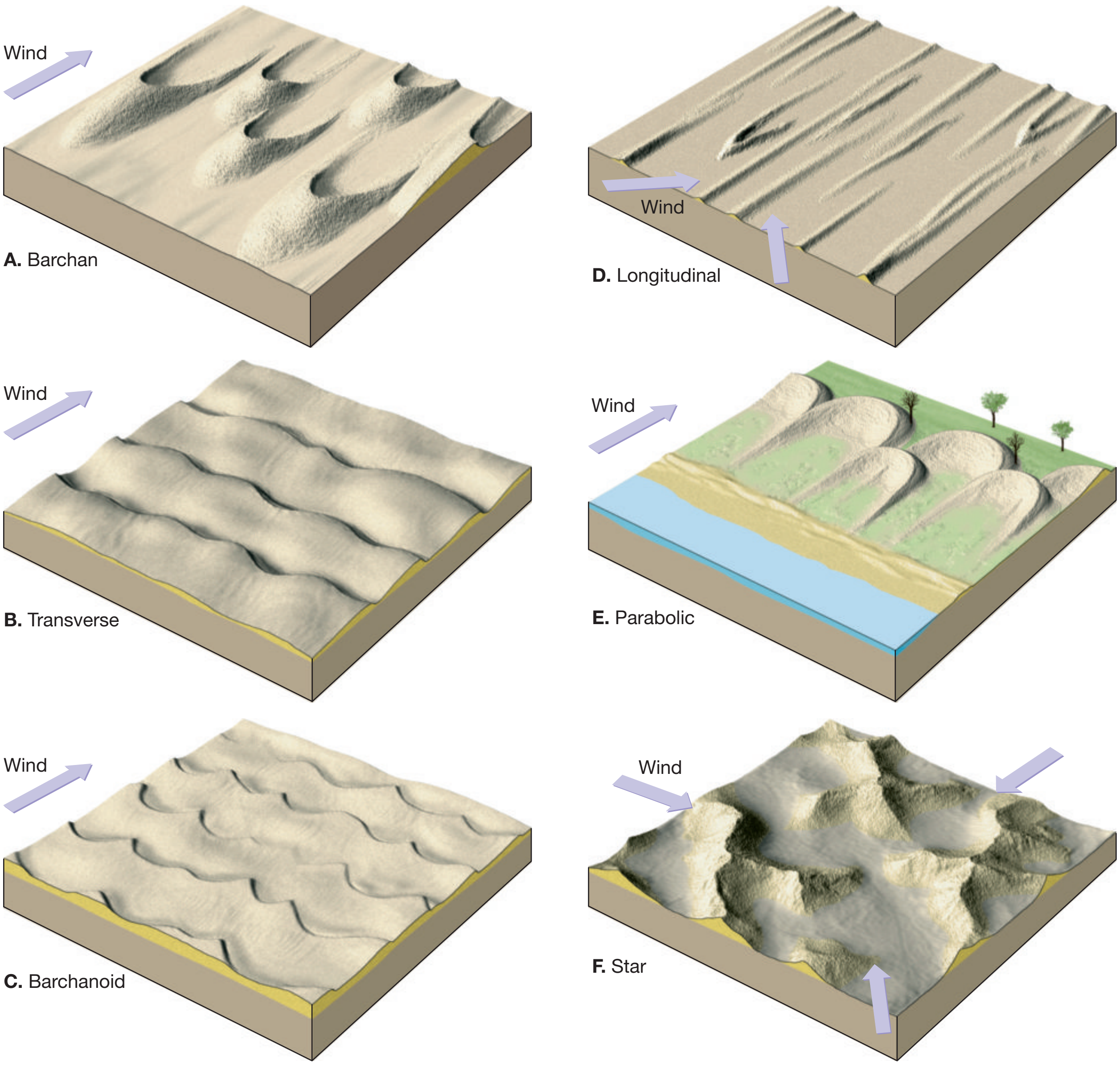


FIGURE 19.19 Sand dune types. **A.** Barchan dunes. **B.** Transverse dunes. **C.** Barchanoid dunes. **D.** Longitudinal dunes. **E.** Parabolic dunes. **F.** Star dunes.

FIGURE 19.20 Barchanoid dunes represent a type that is intermediate between isolated barchans on the one hand and extensive transverse dunes on the other. The gypsum dunes at White Sands National Monument, New Mexico, are an example. (Photo by Michael Collier)

Students Sometimes Ask . . .

Aren't deserts mostly covered with sand dunes?

A common misconception about deserts is that they consist of mile after mile of drifting sand dunes. It is true that sand accumulations do exist in some areas and may be striking features. But, perhaps surprisingly, sand accumulations worldwide represent only a small percentage of the total desert area. For example, in the Sahara—the world's largest desert—accumulations of sand cover only *one-tenth* of its area. The sandiest of all deserts is the Arabian, one-third of which consists of sand.

supplies of sand are limited and the surface is relatively flat, hard, and lacking vegetation. They migrate slowly with the wind at a rate of up to 15 meters (50 feet) per year. Their size is usually modest, with the largest barchans reaching heights of about 30 meters (100 feet) while the maximum spread between their horns approaches 300 meters (1000 feet). When the wind direction is nearly constant, the crescent form of these dunes is nearly symmetrical. However, when the wind direction is not perfectly fixed, one tip becomes larger than the other.

Transverse Dunes In regions where the prevailing winds are steady, sand is plentiful, and vegetation is sparse or absent, the dunes form a series of long ridges that are separated by troughs and oriented at right angles to the prevailing wind. Because of this orientation, they are termed **transverse dunes** (Figure 19.19B). Typically, many coastal dunes are of this type. In addition, transverse dunes are common in many arid regions where the extensive surface of wavy sand is sometimes called a *sand sea.* In some parts of the Sahara and Arabian deserts, transverse dunes reach heights of 200 meters, are 1 to 3 kilometers across, and can extend for distances of 100 kilometers or more.

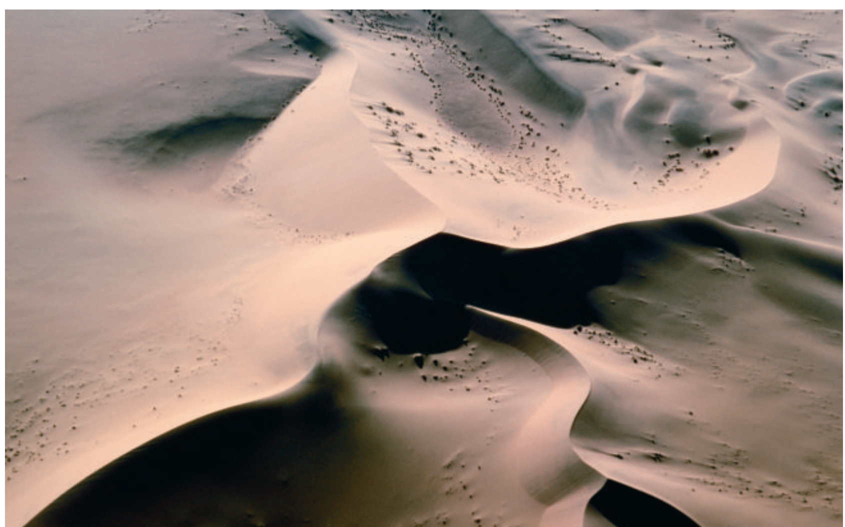
There is a relatively common dune form that is intermediate between isolated barchans and extensive waves of transverse dunes. Such dunes, called **barchanoid dunes,** form scalloped rows of sand oriented at right angles to the wind (Figure 19.19C). The rows resemble a series of barchans that have been positioned side by side. Visitors exploring the gypsum dunes at White Sands National Monument, New Mexico, will recognize this form (Figure 19.20).

Longitudinal Dunes **Longitudinal dunes** are long ridges of sand that form more or less parallel to the prevailing wind and where sand supplies are moderate (Figure 19.19D). Apparently the prevailing wind direction must vary somewhat but still remain in the same quadrant of the compass. Although the smaller types are only 3 or 4 meters high and several dozens of meters long, in some large deserts longitudinal dunes can reach great size. For example, in portions of North Africa, Arabia, and central Australia, these dunes may approach a height of 100 meters (300 feet) and extend for distances of more than 100 kilometers (62 miles).

Parabolic Dunes Unlike the other dunes that have been described thus far, **parabolic dunes** form where vegetation partially covers the sand. The shape of these dunes resembles the shape of barchans except that their tips point into the wind rather than downwind (Figure 19.19E). Parabolic dunes often form along coasts where there are strong onshore winds and abundant sand. If the sand's sparse vegetative cover is disturbed at some spot, deflation creates a blowout. Sand is then transported out of the depression and deposited as a curved rim, which grows higher as deflation enlarges the blowout.

Star Dunes Confined largely to parts of the Sahara and Arabian deserts, **star dunes** are isolated hills of sand that exhibit a complex form (Figure 19.19F). Their name is derived from

FIGURE 19.21 Star dune in the Namib Desert in southwestern Africa. (Photo by Comstock)



the fact that the bases of these dunes resemble multipointed stars. Usually three or four sharp-crested ridges diverge from a central high point that in some cases may approach a height of 90 meters (Figure 19.21). As their form suggests, star dunes develop where wind directions are variable.

Loess (Silt) Deposits

In some parts of the world the surface topography is mantled with deposits of windblown silt, called **loess.** Over periods of perhaps thousands of years, dust storms deposited this material. When loess is breached by streams or road cuts, it tends to maintain vertical cliffs and lacks any visible layers, as you can see in Figure 19.22.

The distribution of loess worldwide indicates that there are two primary sources for this sediment: deserts and glacial outwash deposits. The thickest and most extensive deposits of loess on Earth occur in western and northern China. They were blown here from the extensive desert basins of central Asia. Accumulations of 30 meters (100 feet) are common, and thicknesses of more than 100 meters have been measured. It is this fine, buff-colored sediment that gives the Yellow River (Huang Ho) its name.

In the United States, deposits of loess are significant in many areas, including South Dakota, Nebraska, Iowa, Missouri, and Illinois, as well as portions of the Columbia Plateau in the Pacific Northwest. The correlation between the distribution of loess and important farming regions in the Midwest and eastern Washington State is not just a coincidence because soils derived from this wind-deposited sediment are among the most fertile in the world.

Unlike the deposits in China, which originated in deserts, the loess in the United States (and Europe) is an indirect product of glaciation. Its source is deposits of stratified drift. During the retreat of the ice sheets, many river valleys were choked with sediment deposited by meltwater. Strong westerly winds sweeping across the barren floodplains picked up the finer sediment and dropped it as a blanket on the eastern sides of the valleys. Such an origin is confirmed by the fact that loess deposits are thickest and coarsest on the lee side of such major glacial drainage outlets as the Mississippi and Illinois rivers and rapidly thin with increasing distance from the valleys. Furthermore, the angular, mechanically weathered particles composing the loess are essentially the same as the rock flour produced by the grinding action of glaciers.

Students Sometimes Ask . . .

Where are the largest sand dunes found, and how big are they?

The highest dunes in the world are located along the southwest coast of Africa in the Namib Desert. In places, these huge dunes reach heights of 300 to 350 meters (1000 to 1167 feet). The dunes at Great Sand Dunes National Park in southern Colorado are the highest in North America, rising over 210 meters (700 feet) above the surrounding terrain.

FIGURE 19.22 **A.** This vertical loess bluff near the Mississippi River in southern Illinois is about 3 meters high. (Photo by James E. Patterson) **B.** In parts of China loess has sufficient structural strength to permit the excavation of dwellings. (Photo by Betty Crowell) **C.** This satellite image from March 13, 2003, shows streamers of windblown dust moving southward into the Gulf of Alaska. It illustrates a process similar to the one that created many loess deposits in the American Midwest during the Ice Age. Fine silt is produced by the grinding action of glaciers, then transported beyond the margin of the ice by running water and deposited. Later, the fine silt is picked up by strong winds and deposited as loess. (NASA image)

Summary

- The *concept of dryness is relative;* it refers to any situation in which a water deficiency exists. Dry regions encompass about 30 percent of Earth's land surface. Two climatic types are commonly recognized: *desert,* which is arid, and *steppe* (a marginal and more humid variant of desert), which is semiarid. *Low-latitude deserts* coincide with the zones of subtropical highs in lower latitudes. On the other hand, *middle-latitude deserts* exist principally because of their positions in the deep interiors of large landmasses far removed from the ocean.
- The same geologic processes that operate in humid regions also operate in deserts, but under contrasting climatic conditions. In dry lands *rock weathering of any type is greatly reduced* because of the lack of moisture and the scarcity of organic acids from decaying plants. Much of the weathered debris in deserts is the result of *mechanical weathering*. Practically all desert streams are dry most of the time and are said to be *ephemeral.* Stream courses in deserts are seldom well integrated and lack an extensive system of tributaries. Nevertheless, *running water is responsible for most of the erosional work in a desert.* Although wind erosion is more significant in dry areas than elsewhere, the main role of wind in a desert is in the transportation and deposition of sediment.
- Because arid regions typically lack permanent streams, they are characterized as having *interior drainage.* Many of the landscapes of the Basin and Range region of the western and southwestern United States are the result of streams eroding uplifted mountain blocks and depositing the sediment in interior basins. *Alluvial fans, playas,* and *playa lakes* are features often associated with these landscapes. In the late stages of erosion, the mountain areas are reduced to a few large bedrock knobs, called *inselbergs,* projecting above sediment-filled basins.
- The transport of sediment by wind differs from that by running water in two ways. First, wind has a low density compared to water; thus, it is not capable of picking up and transporting coarse materials. Second, because wind is not confined to channels, it can spread sediment over large areas. The *bed load* of wind consists of sand grains skipping and bouncing along the surface in a process termed *saltation.* Fine dust particles are capable of being carried by the wind great distances as *suspended load.*
- Compared to running water and glaciers, wind is a less significant erosional agent. *Deflation,* the lifting and removal of loose material, often produces shallow depressions called *blowouts.* Wind also erodes by *abrasion*, often creating interestingly shaped stones called *ventifacts. Yardangs* are narrow, streamlined, wind-sculpted landforms.
- *Desert pavement* is a thin layer of coarse pebbles and cobbles that covers some desert surfaces. Once established, it protects the surface from further deflation. Depending upon circumstances, it may develop as a result of deflation or deposition of fine particles.
- Wind deposits are of two distinct types: (1) *mounds and ridges of sand,* called *dunes,* which are formed from sediment that is carried as part of the wind's bed load; and (2) extensive *blankets of silt*, called *loess,* that once were carried by wind in *suspension.* The profile of a dune shows an asymmetrical shape with the leeward (sheltered) slope being steep and the windward slope more gently inclined. The *types of sand dunes* include (1) *barchan dunes;* (2) *transverse dunes;* (3) *barchanoid dunes;* (4) *longitudinal dunes;* (5) *parabolic dunes;* and (6) *star dunes.* The thickest and most extensive deposits of loess occur in western and northern China. Unlike the deposits in China, which originated in deserts, the loess in the United States and Europe is an indirect product of glaciation.

Review Questions

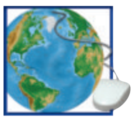
1. How extensive are the desert and steppe regions of Earth?
2. What is the primary cause of subtropical deserts? Of middle-latitude deserts?
3. In which hemisphere (Northern or Southern) are middle-latitude deserts most common?
4. Why is the amount of precipitation that is used to determine whether a place has a dry climate or a humid climate a variable figure? (See Box 19.1, p. 518)
5. *Deserts are hot, lifeless, sand-covered landscapes shaped largely by the force of wind.* The preceding statement summarizes the image of arid regions that many people hold, especially those living in more humid places. Is it an accurate view?
6. Why is rock weathering reduced in deserts?
7. As a permanent stream such as the Nile River crosses a desert, does discharge increase or decrease? How does this compare to a river in a humid region?
8. What is the most important erosional agent in deserts?
9. Why is sea level (ultimate base level) not a significant factor influencing erosion in desert regions?
10. Why is the Aral Sea shrinking (see Box 19.2, p. 521)?
11. Describe the features and characteristics associated with each of the stages in the evolution of a mountainous desert. Where in the United States can these stages be observed?
12. Describe the way in which wind transports sand. During very strong winds, how high above the surface can sand be carried?

13. Why is wind erosion relatively more important in arid regions than in humid areas?
14. In what ways do human activities contribute to desertification (see Box 19.4, p. 527)?
15. What factor limits the depths of blowouts?
16. Briefly describe two hypotheses used to explain the formation of desert pavement.
17. How do sand dunes migrate?
18. List three factors that influence the form and size of a sand dune.
19. Six major dune types are recognized. Indicate which type of dune is associated with each of the following statements.
    - **a.** dunes whose tips point into the wind
    - **b.** long sand ridges oriented at right angles to the wind
    - **c.** dunes that often form along coasts where strong winds create a blowout
    - **d.** solitary dunes whose tips point downwind
    - **e.** long sand ridges that are oriented more or less parallel to the prevailing wind
    - **f.** an isolated dune consisting of three or four sharp-crested ridges diverging from a central high point
    - **g.** scalloped rows of sand oriented at right angles to the wind
20. Although sand dunes are the best-known wind deposits, accumulations of loess are very significant in some parts of the world. What is loess? Where are such deposits found? What are the origins of this sediment?

Key Terms

abrasion (p. 528)
alluvial fan (p. 523)
bajada (p. 524)
barchan dune (p. 531)
barchanoid dune (p. 531)
bed load (p. 525)
blowout (p. 526)
cross beds (p. 530)
deflation (p. 526)
desert (p. 517)
desert pavement (p. 526)
dune (p. 529)
ephemeral stream (p. 520)
inselberg (p. 524)
interior drainage (p. 522)
loess (p. 532)
longitudinal dune (p. 531)
parabolic dune (p. 531)
playa (p. 524)
playa lake (p. 524)
rainshadow desert (p. 519)
saltation (p. 525)
slipface (p. 530)
star dune (p. 531)
steppe (p. 517)
suspended load (p. 525)
transverse dune (p. 531)
ventifact (p. 528)
yardang (p. 528)

Web Resources



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- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

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