

# CHAPTER 9

## DESERTS

### 1. INTRODUCTION

**1.1** I might define a *desert* as a land area characterized by sparse and infrequent rainfall. I wonder what images pop into your mind when I mention deserts: vast expanses of dry, rocky, rugged land? enormous shifting sand dunes? Both of these images are good representations of many deserts, but I think it's important to point out that

- most deserts have at least some vegetation, and
- sand dunes constitute only a small percentages of the area of most deserts.

**1.2** It was once generally believed that the land surface of deserts is shaped mainly by the wind. But it's clear now *that except for areas of sand dunes, the desert landscape is shaped almost entirely by running water rather than by wind.* It rains, albeit infrequently, even in the driest of deserts. And in very dry deserts the vegetation is so sparse as not to provide much stability to the surficial layer of regolith, so the running water can readily mobilize the regolith and shape the landscape.

**1.3** In the Atacama Desert in Chile the average annual rainfall is between one and two millimeters, and no rain at all falls for years at a time. But when it does rain in such a desert, a lot of rain—as much as several centimeters—can fall in a short time; that's when almost all of the sediment movement takes place.

**1.4** Another misconception we Americans tend to have about deserts is that they are mountainous areas with characteristic relief made up of mountain ranges with intervening basins. In fact *most of the desert areas of the world are not mountainous*; they are broad plains of relatively low relief, except for large sand dunes in certain places.

### 2. CLASSIFICATION OF DESERTS

**2.1** Deserts can conveniently be classified into three kinds:

**High-latitude deserts.** At high latitudes, temperatures are so low most of the year, and sources of atmospheric moisture are so far away, that rainfall is very low. Water present near the surface is frozen for most or all of the year. In a sense, the surface of the northern part of the Greenland Ice Sheet and the interior part of the Antarctic Ice Sheet are deserts!

**Mid-latitude deserts.** In temperate latitudes, deserts form only where for one (or both) of two reasons rainfall is scanty over large areas. Rainfall can be low because an area is located in the interior of a large continent, far away from marine sources of atmospheric moisture, like the interior of Asia. Or rainfall can be low because mountain ranges located upwind extract most of the moisture from the air. Such deserts might be called *rain-shadow deserts*. The deserts of the southwestern United States are of this kind.

**Low-latitude deserts.** In the subtropical high-pressure belts of both hemispheres (the so-called horse latitudes), the atmosphere undergoes widespread subsidence as a consequence of broad patterns of the general circulation of the atmosphere, so cloudiness and precipitation is uncommon. Most of the great deserts of the world, in North Africa and the Middle East, are of this kind.

### 3. A BRIEF SUMMARY OF DESERT FEATURES

#### 3.1 Introduction

**3.1.1** Because eolian transport of sand, and the construction of eolian dunes large and small, is perhaps the most striking characteristic of deserts (even though, as noted above, fluvial sediment transport is much more effective in shaping the landscapes of deserts), I'll concentrate in the following sections on *eolian saltation and eolian dunes*. But in this section I'll mention just briefly several other aspects of deserts.

#### 3.2 Alluvial fans

**3.2.1** An *alluvial fan* is a *fan-shaped or cone-shaped body of loose sediment deposited at the foot of a steep stream valley*. Alluvial fans usually consist mostly of sand and gravel. Fans are deposited because the slope of the stream, and therefore the sediment-transporting ability of the stream, decreases abruptly where the stream leaves its mountain channel and spreads into a valley. At the head of the fan, the stream passes from being laterally confined to laterally unconfined, so on average it becomes wider and shallower, and therefore of gentler slope—although the transition is not really as abrupt as I indicated above.

**3.2.2** The contrast in slope between the confined mountain stream and the unconfined fan surface is greatest in the very early stages of fan development, when there's only a small fan at the base of a steep mountain front, and much less in the later stages, when the fan has built to greater size and the stream has had a chance to cut a deep canyon and extend its headwaters far into the mountain mass.

**3.2.3** Once on the fan, the stream progrades the fan locally, and in doing so the elevation of the stream bed is raised somewhat above the level of the adjacent fan surface. (By *progradation* I mean the tendency for the depositional surface to be built forward, in the direction of sediment transport.) At some point the stream

shifts its position to a lower area of the fan. In this way, over a long time period the stream sweeps irregularly across the entire fan, building it in a symmetrical, conical shape.

**3.2.4** Alluvial fans are characteristic of deserts with high relief, especially in the southwestern US, but they are not common in many other deserts. You should also keep in mind that *alluvial fans are not restricted to arid or semiarid regions*: they form even in humid regions where there is high relief and rapid weathering. In such areas, however, alluvial fans tend to be heavily vegetated and not as noticeable.

### **3.3 Ventifacts**

**3.3.1** Rigid solid surfaces tend to be abraded by the impact of flying sand grains. The upwind-facing surfaces of outcropping bedrock or pieces of gravel are abraded to smooth and sometimes fluted surfaces. Such rocks are called *ventifacts*, or wind-worn stones. Loose pieces of gravel sometimes show a faceted shape formed by abrasion from two or three different directions—either by variability of wind direction or shifting of the position of the clast relative to the prevailing sand-transporting wind direction.

### **3.4 Desert Pavement**

**3.4.1** On old alluvial fans it's common to see a ground surface with a strikingly densely packed veneer of gravel. The substrate beneath consists of much finer sediment as well as gravel. The explanation is that the surface of an alluvial fan can become stranded, or cut off from fresh supply of sediment. This happens whenever there is tectonic uplift of the fan, causing the streams to be incised into the fan. Then slow *deflation* (*removal of sediment by wind action*) winnows the finer part of the surficial sediment, leaving only the coarsest fraction as a surficial residue. If you dig just below the surficial coarse layer you find a mixture of coarse material with much finer sediment. Only if the coarse surface layer is somehow disturbed can the wind act upon that underlying fine material.

### **3.5 Desert Varnish**

**3.5.1** Rock surfaces in the desert commonly show a dark coating, dark brown to almost black and sometimes even with a suggestion of darkest violet. The coatings, a small fraction of a millimeter thick (0.05–0.1 mm), are known from actual chemical analyses to be rich in iron and especially manganese, along with aluminum, silicon, and oxygen, but these elements seem not to be well crystallized into minerals.

**3.5.2** Rocks most susceptible to desert varnish are relatively resistant to weathering: mafic and felsic volcanics, metamorphics, and well cemented sandstones. Rocks like felsic intrusives, which tend in deserts to weather fairly readily by granular disintegration, don't show good desert varnish, because the surfaces are degraded too fast by mechanical weathering. The same is true of limestones and even dolostones, because they weather by solution too fast.

**3.5.3** The source of the Fe and Mn, as well as the mode of precipitation, are not entirely clear. The general consensus seems to be that Fe and Mn can be derived either from the interior of the rock itself or from soil in which rock fragments rest. (Other things—rock type and locality—being equal, rock fragments in regolith show better desert varnish than bedrock.)

**3.5.4** Films of moisture must be invoked for transport of the Fe and Mn in solution; rainwater is an obvious possibility, but coatings of dew are likely to be even more important, because most desert rocks are wet for a much greater part of the time from dew than from rain. The Fe and Mn in solution could be transported by actual flow of the film, or by diffusion across it. The details of chemistry are not yet clear.

**3.5.5** By various lines of evidence it's known that the time scales for development of a good coating of desert varnish vary greatly, from just a few decades in the most favorable circumstances to many centuries or even millennia.

### **3.6 Playas**

**3.6.1** In geomorphological usage, a *playa* is *the barren, flat, and usually dry area at the lowest part of a basin of interior drainage*. (In Spanish, *playa* means just *beach* or *shore*.) The typical playa is dry most of the time, except for occasional inundation by infrequent heavy rain in the watershed area. Playas vary in size from those you can walk across in a few minutes to those many kilometers across. With increasing frequency and magnitude of rainfall in the drainage basin, playas grade over into what might better be termed *ephemeral lakes*, and then into permanent interior-drainage lakes.

**3.6.2** Most playa surfaces are virtually nonvegetated, except possibly at the very periphery, where relatively salt-free water emerges from drainage from the distal slopes of alluvial fans, which typically terminate at the playa edge. The lack of vegetation is clearly related to the elevated content of salts in the sediments of the playa.

**3.6.3** The nature of playa surfaces varies widely, depending partly upon the ratio of dissolved load (salts in solution) to fine particulate sediment (mainly suspended load) in the flows reaching the playa, and partly upon the groundwater regime of the playa. Some playas, especially those that are topographically closed but have throughgoing flow of groundwater, are dry except soon after rains,

because the water can drain out of the basin through an aquifer. Such playas have little or no salt in their sediments. Other playas, which are closed with respect to groundwater flow as well as to topography, tend to be moist long after rains, especially where the groundwater table, or at least the capillary fringe thereof, is always fairly near the playa surface. Such playas are characterized by much salt in their sediments, and some consist mostly or entirely of evaporites. (Evaporites are sediment deposits that originate from partial or complete evaporation of water that contains salts in solution.) The salt content of such playas is derived partly from weathering of rocks in the watershed (that salt may be from pore waters originally included in sedimentary rock or it may be from constituents of the minerals themselves) or from washing out of atmospheric salts, ultimately derived from the ocean. That not all evaporitic playas show the same content is good evidence that the salt content in the watershed is usually the more important of the two sources. Halite, gypsum, and borates are some of the common compositions of playa evaporites. The floor of Death valley is probably the most-visited playa, still in its natural state, in the United States.

#### 4. SALTATION

**4.1** Earlier in the course I tried to give you a qualitative picture of the nature of sediment movement by flows of water. You learned that sediment is moved by water as bed load and as suspended load. The picture of sediment transport by air is somewhat different. This is basically because *the ratio of sediment density to fluid density is almost three orders of magnitude greater in air than in water*. This means that *once a sediment particle is set in motion by a flow of air, the particle tends to follow a trajectory that is largely independent of the details of turbulence in the air*, because of the great relative inertia of the particle. In water, on the other hand, sediment particles in transport tend to follow rather closely the patterns of motion in the water itself.

**4.2** The forces the wind exerts on sediment particles resting on the land surface are not greatly different from those exerted by flowing water, and particles can be set into motion as bed load or lifted into suspension, just as in flowing water. But particles of sand size or greater, which are set into motion as bed load, are able to make much stronger impacts with the sediment surface, because of the relatively slight cushioning effect of the fluid. The consequence is far greater importance of ballistic or collisional effects in eolian transport. This is manifested in a characteristic mode of transport called *saltation*.

**4.3** The term *saltation* is used for *a mode of particle movement in which trajectories of particles show take-off from the bed at moderate to steep angles and descent to the bed at small angles*. Figure 9-1 shows a typical saltation trajectory taken by a saltating grain of sand in air. Saltation trajectories are rather regular, and then they show little of the sinuosity that might be expected from

passage through turbulent eddies. This is because of the typically large ratio of particle density to fluid density: the particles have great relative inertia, and they can cruise almost unaffected through eddies with rather different local fluid velocities.

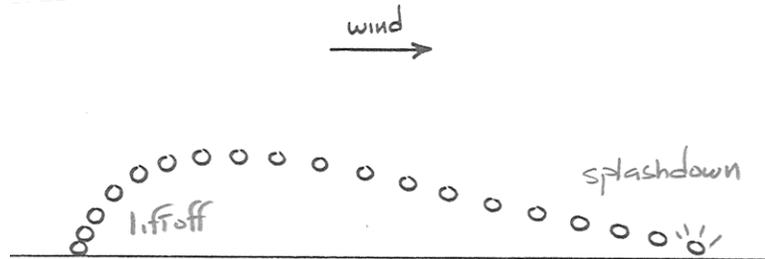


Figure 9-1. A typical saltation trajectory of a sand particle moved by the wind.

**4.4** Saltation is the dominant mode of particle movement when a strong wind blows over a sand surface. Except in the very strongest winds, the *saltation heights* attained by the saltating grains seldom exceeds a meter, and the *saltation lengths* are mostly less than a few meters. There is, of course, a continuous distribution of jump heights and jump lengths, from zero to the maximum. There's also wide variability in take-off angles: they range from just a few tens of degrees to vertical. After colliding with some particularly immovable bed grains, some saltating grains even take off with an upstream component to their motion!

**4.5** If you are lucky enough to be out on a dry sand surface during a strong wind, take the risk of getting some sand in your eyes and nose and mouth, and get down for a horizontal view at an eye level of a few tens of centimeters above the surface. You would see a hazy layer of saltating grains, which tails off imperceptibly upward. This *well defined layer of saltating grains* is called the **saltation carpet**. If you then looked downward at the sand surface, you would see *an abundance of surface grains being pushed and jogged along for short distances*, just one or a few grain diameters at a time, presumably by being struck by saltating grains. That mode of movement is called **surface creep**—but there is actually no sharp break between surface creep and saltation.

**4.6** To see individual saltation trajectories nicely you would have to be out there at night with a strobe light. The best thing to do is shine the strobe light straight down at the bed through a horizontal slit oriented parallel to flow; that way you see only a thin slice of the saltation carpet. The effect is striking. You could easily do the same thing in a homemade wind tunnel, which doesn't have to

be any bigger than tabletop size. The most common kind of wind tunnel for studies of sand movement (Figure 9-2) consists of a duct with a flared entrance, which passes into a large collection box with an exhaust fan on the other wall. You can start with the sand in the duct, or you can shower it into the upstream end through a slit in the roof of the duct.

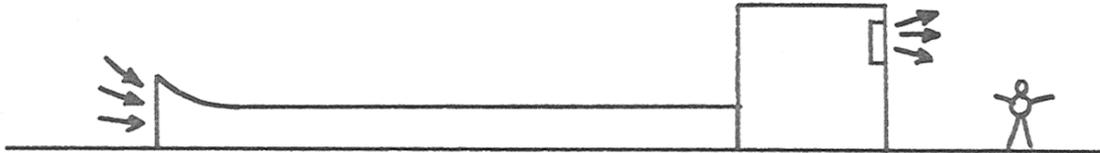


Figure 9-2. A wind tunnel of suction type.

**4.7** Many aspects of saltation are not well understood. Among these is *the mechanism that causes the initial rise of the grains*. Two different effects might be important:

**Aerodynamic lift forces.** This is not the place to discuss the intricacies of the Bernoulli equation, which expresses the relationship between fluid pressure and fluid velocity in any flowing fluid. Suffice it to say that along any flow line in the flow there is an inverse relationship between the pressure and the velocity: where the velocity is high, the pressure tends to be low, and where the velocity is low, the pressure tends to be high. This is what makes airplanes fly (Figure 9-3A): the shape of the wing section is such that the air travels a shorter distance around the lower surface of the wing than around the upper surface, so the velocity is lower and the pressure is higher. This pressure difference between the lower surface and the upper surface of the wing is called *lift*. The same is true of a sand particle resting on a sediment surface (Figure 9-3B): the velocity is relatively low around the base of the particle and relatively high at its top, so there is *a net upward pressure force in addition to the downwind drag of the wind*.

**Ballistic collisions between the moving particle and the bed particles.** When a flying particle makes impact with the bed, it imparts part of its momentum to one or more bed particles. One or more of the bed particles is likely thereby to be launched into motion above the bed. Take-off velocities and angles depend in some very complicated way upon the local geometry of arrangement of the bed grains and upon the velocity and location of impact.

4.8 Despite much research over the years, the relative importance of these two effects—*aerodynamic lift and particle collisions*—is still controversial.

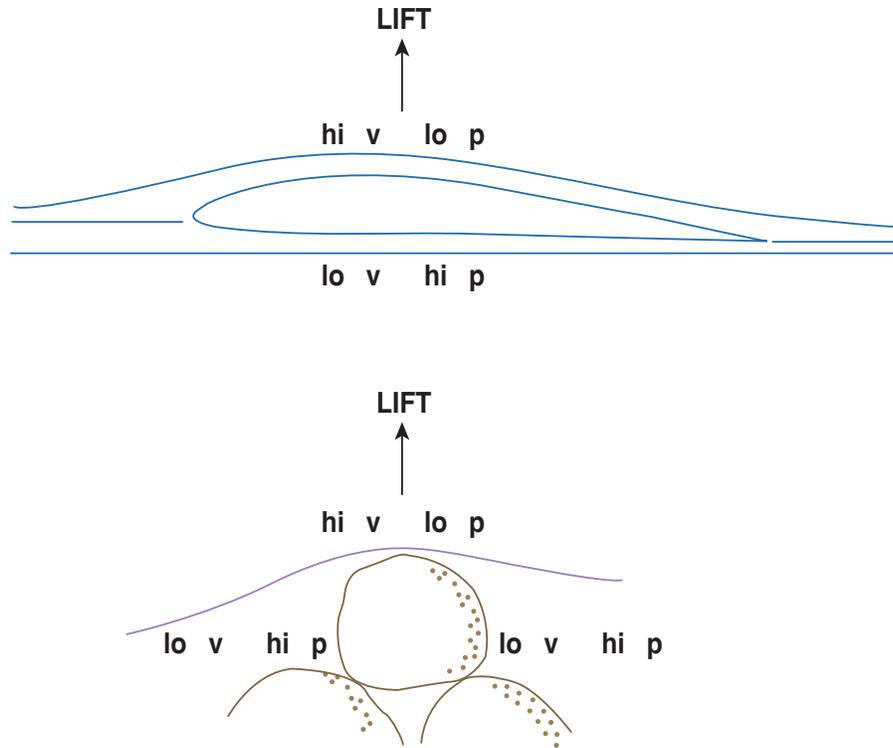


Figure by MIT OCW

Figure 9-3. Aerodynamic lift forces. A) On an airplane wing. B) On a sediment particle.

4.9 An interesting aerodynamic aspect to saltation has to do with *the rotation rates of saltating particles*. Ultra-high-speed motion pictures have revealed strikingly high spin rates of hundreds of revolutions per second. The sense of spin is such that that the top of the particle moves faster in the downstream direction than the bottom of the particle (Figure 9-4). The origin of such high rates of spin is still a mystery. But it's clear that *the spinning motion gives rise to a non-negligible additional lift force on the particle*, by what's known as the **Magnus effect**: the rotation of the grain alters the streamline pattern around it in such a way that instead of the pattern being symmetrical about the grain, the streamlines are closer together above the grain than below it (Figure 9-5). By the Bernoulli equation, this means that the fluid pressure at the grain surface is smaller above the grain than below, causing a net lift force. It's the same effect that makes for curve balls, and for those annoying slices and hooks.

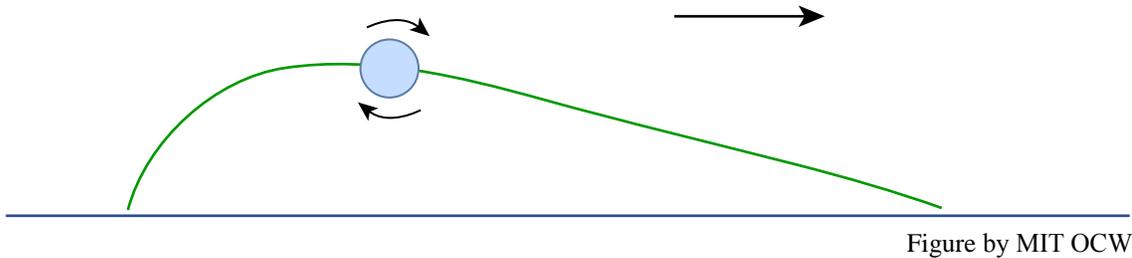


Figure 9-4. The sense of rotation of a saltating particle.

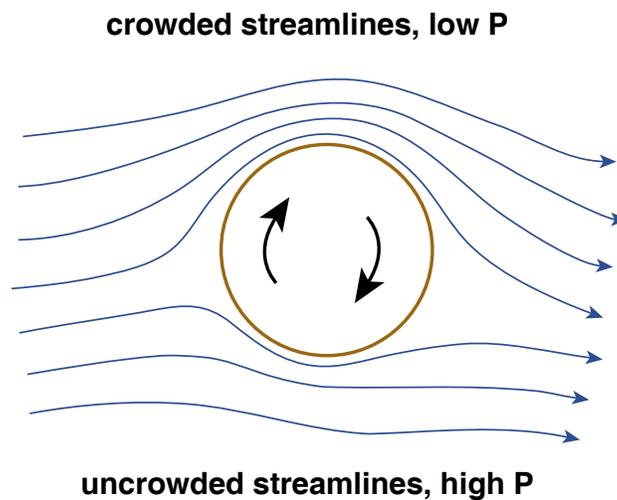


Figure 9-5. The Magnus effect.

**4.10** Except in the very strongest of winds, saltating sand grains seldom attain heights greater than somewhere between one and two meters. So the Hollywood conception of a sand storm, in which the protagonist steps out of his tent into a blinding, choking cloud, is all wrong: in a real sand storm the air at one's eye level is clear, but one's legs are being bombarded by zillions of saltating sand grains. Hollywood sand storms are really dust storms, which can happen only where there's not only a strong wind but also a freshly available surficial layer of fine sediment, as from a recent flow of water after a heavy rain. *Dust storms aren't very common in deserts*, because these fresh supplies of sediment are made available to the wind so infrequently.

## 5. EOLIAN RIPPLES AND EOLIAN DUNES

**5.1** You learned earlier that when a current of water flows over a bed of loose sand, if the current is strong enough to move some of the sediment several kinds of geometrical features, called bed forms, are molded by the flow. The same is true for flows of air over loose sediment. And in fact, just as in water flows, two different kinds of bed forms, *ripples* and *dunes*, are formed at widely different scales. A dynamical instability of some kind, whereby a planar sand surface is unstable to small disturbances, is involved in both cases, water and wind. The dynamics behind these instabilities is just as mysterious in the case of wind as in the case of water. It's not even known for sure whether subaqueous and subaerial ripples are the same dynamical kind of feature, and whether subaqueous and subaerial dunes are the same dynamical kind of feature.

**5.2** Here's another home experiment for you to try. (I promise you that this will be the last home experiment I propose this semester!) It would be easy to build a home wind tunnel. (See Figure 9-2 above.) Just nail four wide pine boards together to make a duct several feet long, and arrange the downwind end to pass into a hole in a large box. In the other wall of the box, mount a window fan. Put a layer of sand in the duct, turn on the fan, and you have eolian transport. (It would help to improve the design in three ways: put a couple of Plexiglas windows in the duct so you can watch the sand move; make the upper surface of the duct removable so you can get at the sand and photograph it easily; and arrange a flap board against the downwind side of the fan to control the wind speed.)

**5.3** Gradually increase the wind speed over a planar sand surface in your duct until the sand grains just begin to move. Very soon after that, fully developed saltation sets in. If then you gradually decreased the wind speed again, you would find that the minimum wind speed needed to maintain already existing saltation is much less than the wind speed needed to initiate saltation. A physicist would call this a *hysteresis effect*. (Can you recall an earlier example of hysteresis in this course?) These two wind speeds represent what are called the *saltation threshold* and the *fluid threshold*, respectively.

**5.4** Crank up the wind again until there's saltation. You would have to wait only a matter of minutes until the originally planar sand surface becomes molded into a strikingly regular series of wind-transverse rounded ridges and troughs called *wind ripples* or *eolian ripples*. The typical spacing of wind ripples is of the order of several centimeters, although they get bigger in poorly sorted and/or coarser sediment. They shift very slowly in the downwind direction, by movement of sediment up the upwind flanks and deposition of that sediment on the downwind flanks.

**5.5** There's a tendency for the particle size to be slightly coarser on the crests of the ripples and slightly finer in the troughs. Long ago R.A. Bagnold, a pioneer in the study of eolian sediment transport, devised a spectacularly visual

demonstration of this effect by making wind ripples in a thoroughly mixed sand of two different colors in a wind tunnel: as the ripples develop, the bed surface resolves itself into alternating stripes of the two different colors right before one's eyes!

**5.6** Eolian dunes are not as easy to make in experimental wind tunnels, because their minimum scale is too big. Almost everything we know about dunes is from studies in the field. One of the big problems in the studying of eolian dunes is that *there aren't many places in the world characterized by really steady winds*: obviously the wind speed varies with time, but in most places the wind direction changes substantially too. Nobody really knows what the reference case of dunes formed by a steady wind over a full sand surface of effectively infinite extent looks like.

**5.7** Eolian dunes take many different shapes, and there is no generally accepted classification. One reads about linear dunes, longitudinal dunes, crescentic dunes, seif dunes, oblique dunes, barchan dunes, star dunes, and many others. I think a fairly satisfactory but simplified way of classifying dunes is to recognize three kinds of dunes formed in full sand beds depending on orientation relative to a dominant sand-moving wind:

**transverse dunes**, oriented normal to the wind

**longitudinal dunes** (also called **seif dunes**), oriented parallel to the wind

**oblique dunes**, oriented oblique to the wind.

**5.8** It's not even clear whether these three basic kinds are dynamically different from one another or not. Dunes formed by winds blowing from various directions without a dominant sand-movement direction are called *star dunes*. Star dunes are found where sand-transport paths converge to form a sand "sink" or sand-storage area. Finally, dunes formed in areas where there is not enough sand to keep troughs from being floored by immobile substrate take a characteristic crescent shape are called *barchan dunes*. There's a continuous transition in geometry from barchan dunes to transverse dunes as the thickness of the sand increases relative to dune dimensions, so that less and less of the troughs expose immobile substrate.

**5.9** Of course, dunes are found not just in deserts. *Coastal dunes* are common along many shorelines where onshore winds pick up beach sand and carry it inland to form belts of dunes, narrow or wide. The prerequisite for any area of sand dunes is a source of sand. In deserts that source might be fluvial sediment freshly deposited where a river finally loses all of its water by infiltration into the river bed, or just an area where sand from sandstone bedrock is freed by slow weathering.

**5.10** If the sand supply is abundant and the transport is consistently in one direction away from the source, enormous areas of deserts can be covered with mobile sand. Such areas are usually picturesquely called *sand seas*. Sand seas are especially prominent in North Africa and the Arabian Peninsula.

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