12

AEOLIAN LANDSCAPES

Where conditions are dry and the ground surface bare, wind is a forceful instrument of erosion and deposition. This chapter covers:

- places where wind is an important geomorphic agent
- landforms fashioned by wind erosion
- landforms fashioned by wind deposition
- humans and wind processes

Wind in action

> As an agent of transport, and therefore of erosion and deposition, the work of the wind is familiar wherever loose surface materials are unprotected by a covering of vegetation. The raising of clouds of dust from ploughed fields after a spell of dry weather and the drift of wind-swept sand along a dry beach are known to everyone. In humid regions, except along the seashore, wind erosion is limited by the prevalent cover of grass and trees and by the binding action of moisture in the soil. But the trials of exploration, warfare and prospecting in the desert have made it hardly necessary to stress the fact that in arid regions the effects of the wind are unrestrained. The 'scorching sand-laden breath of the desert' wages its own war on nerves. Dust-storms darken the sky, transform the air into a suffocating blast and carry enormous quantities of material over great distances. Vessels passing through the Red Sea often receive a baptism of fine sand from the desert winds of Arabia; and dunes have accumulated in the Canary Islands from sand blown across the sea from the Sahara.
>
> (Holmes 1965, 748–9)

AEOLIAN ENVIRONMENTS

Wind is a geomorphic agent in all terrestrial environments. It is a potent agent only in dry areas with fine-grained soils and sediments and little or no vegetation. The extensive sand seas and grooved bedrock in the world's arid regions attest to the potency of aeolian processes. More local wind action is seen along sandy coasts and over bare fields, and in alluvial plains containing migrating channels, especially in areas marginal to glaciers and ice sheets. In all other environments, wind activity is limited by a protective cover of vegetation and moist soil, which helps to bind soil particles together and prevent their being winnowed out and carried by the wind, and only in spaces between bushes and on such fast-drying surfaces as beaches can the wind free large quantities of sand.

Deserts are regions with very low annual rainfall (less than 300 mm), meagre vegetation, extensive areas of bare and rocky mountains and plateaux, and alluvial plains that cover about a third of the Earth's land surface (Figure 12.1). Many deserts are hot or tropical, but some polar regions, including Antarctica, are deserts because they are dry. Aridity forms the basis of classifications of deserts. Most classifications use some combination of the number of rainy days, the total annual rainfall, temperature, humidity, and other factors. In 1953, Peveril Meigs divided desert regions on Earth into three categories according to the amount of precipitation they receive:

1 extremely arid lands have at least 12 consecutive months without rainfall;
2 arid lands have less than 250 mm of annual rainfall;

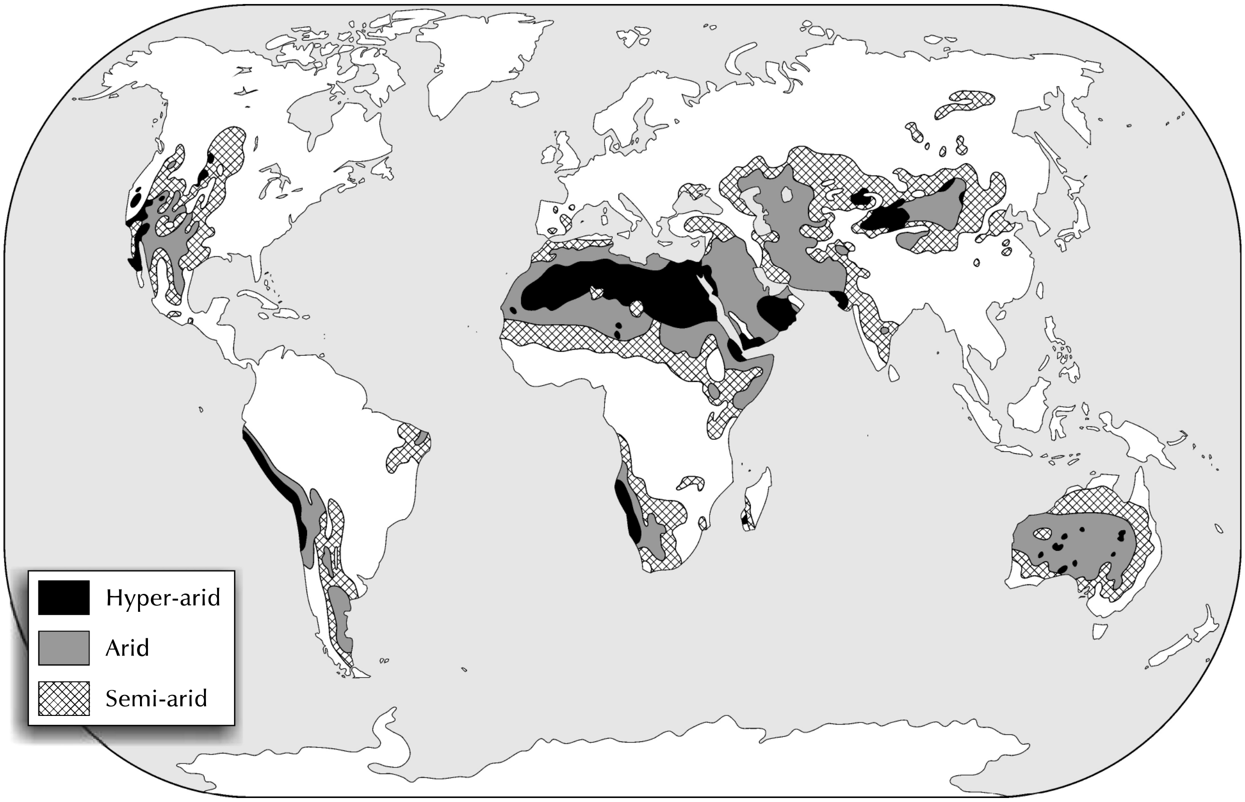

Figure 12.1 The world's deserts.
Source: Adapted from Thomas (1989)

Table 12.1 Degrees of aridity defined by an aridity index

Aridity type	*Aridity index*	*Land area in category (per cent)*
Hyperarid	<0.05	7.5
Arid	0.50–0.20	12.1
Semi-arid	0.20–0.50	17.7
Dry subhumid	0.50–0.65	9.9

3 semi-arid lands have a mean annual precipitation of between 250 and 500 mm.

Arid and extremely arid land are deserts; semi-arid grasslands mostly prairies or steppes. UNEP uses a different index of aridity, defined as

$$AI = PE/P$$

where PE is the potential evapotranspiration and P is the average annual precipitation (Middleton and Thomas 1997). Four degrees of aridity derive from this index (Table 12.1).

Although wind action is an important process in shaping desert landforms, desert landform assemblages vary in different tectonic settings. These regional differences are brought out in Table 12.2, which shows the proportion of landforms in the tectonically active south-west USA and in the tectonically stable Sahara.

Table 12.2 Landforms assemblages in deserts of the south-west USA and the Sahara

Landform	*South-west USA (per cent)*	*Sahara (per cent)*
Desert mountains	38.1	43.0
Playas	1.1	1.0
Desert flats	20.5	10.0
Bedrock fields (including hamadas)	0.7	10.0
Regions bordering through-flowing rivers	1.2	1.0
Dry washes (ephemeral stream beds)	3.6	1.0
Alluvial fans and bajadas	31.4	1.0
Sand dunes	0.6	28.0
Badlands	2.6	2.0
Volcanic cones and fields	0.2	3.0

Source: Adapted from Cooke *et al.* (1993, 20)

AEOLIAN EROSIONAL FORMS

Landforms resulting from wind erosion are seldom preserved except in arid areas. In alluvial plains and beaches, subsequent action by rivers and by waves erases traces of aeolian erosion. In arid areas, other denudational agents are often weak or absent and fail to destroy erosional landforms. The chief erosional forms in drylands caused by wind erosion are lag deposits, desert pavements, ventifacts, yardangs, and basins (see Livingstone and Warren 1996; Breed *et al.* 1997; Goudie 1999).

Lag deposits and stone pavements

Deflation winnows silt and fine sand, lowering the level of the ground surface and leaving a concentrated layer of rock and coarse sand that acts as a protective blanket. Such thin veneers of gravel, or coarser material, that overlie predominantly finer materials are called **lag deposits** (Plate 12.1). Lag deposits cover a significant proportion of the world's deserts, but they also occur in other environments with little vegetation, including mountains and periglacial zones. The coarse material has several local names – gibber in Australia, desert armour in North America, and *hammada*, *serir*, and *reg* in the Arab world.

Lag deposits may result from the deflation of poorly sorted deposits, such as alluvium, that contain a mix of gravel, sand, and silt. The wind removes the finer surface particles, leaving a blanket of material too coarse to undergo deflation. The blanket shields the underlying finer materials from the wind. However, other processes can lead to the concentration of coarse particles on bare surfaces – surface wash, heating and cooling cycles, freezing and thawing cycles, wetting and drying cycles, and the solution and recrystallization of salts.

Where the stone cover is continuous (and the particles generally flat), surfaces covered by lag deposits are called **stone pavements**, but they go by a variety of local

Plate 12.1 Lag deposits lying on a stone pavement, Dhakla, Western Desert, Egypt. (*Photograph by Tony Waltham Geophotos*)

names – desert pavements in the USA, gibber plains in Australia, *gobi* in Central Asia, and *hammada*, *reg*, or *serir* in the Arab world. *Hammada* is rocky desert, in which the lag consists of coarse, mechanically weathered regolith. *Serir* is pebbly desert with a lag of rounded gravel and coarse sand produced by deflation of alluvial deposits.

Deflation hollows and pans

Deflation can scour out large or small depressions called **deflation hollows** or **blowouts**. Blowouts are the commonest landforms produced by wind erosion. They are most common in weak, unconsolidated sediments. In size, they range from less than a metre deep and a few metres across, through enclosed basins a few metres deep and hundreds of metres across (pans), to very large features more than 100 m deep and over 100 km across. They are no deeper than the water table, which may be several hundred metres below the ground surface, and may attain diameters of kilometres.

Pans are closed depressions that are common in many dryland areas and that seem to be at least partly formed by deflation (Figure 12.2; Plate 12.2). In size, they range from a few metres wide and only centimetres deep, to kilometres across and tens of metres deep. The largest known pan, which was discovered in eastern Australia, is 45 km wide. Pans are prominently developed in southern Africa, on the High Plains of the USA, in the Argentinian pampas, Manchuria, western and southern Australia, the west Siberian steppes, and Kazakhstan (Goudie 1999). They sometimes have **clay dunes** or **lunette dunes** formed on their leeside that are composed of sandy, silty, clayey, and salty material from the pan floor. The presence of a lunette is a sure sign that a pan has suffered deflation. The evolution of pans is a matter of debate (Box 12.1).

Deflation appears to have played a starring role in scooping out great **erosional basins**, such as the large oasis depressions in the Libyan Desert. However, such large basins are almost certain to have had a complex evolution involving processes additional to deflation, including tectonic subsidence. The deepest of such basins is the Qattara Depression in northern Egypt, which is cut into Pliocene sediments. At its lowest point, the Qattara Depression lies 134 m below sea level.

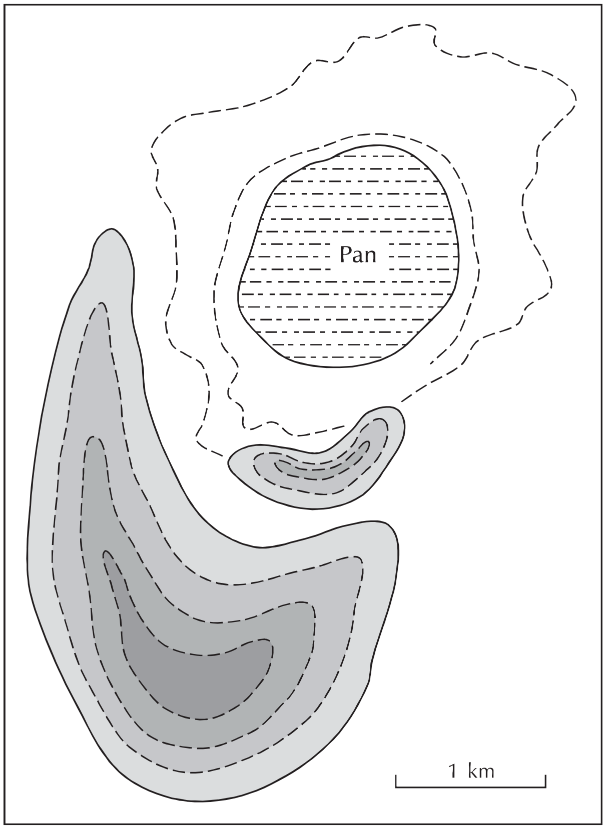

Figure 12.2 A pan in southern Africa.
Source: Adapted from Grove (1969)

Yardangs and *Zeugen*

Yardangs are normally defined as spectacular streamlined, sharp and sinuous ridges that extend parallel to the wind, and are separated by parallel depressions. They are sometimes said to resemble upturned ships' hulls. Yet the form of yardangs varies. Two size classes are distinguished – mega-yardangs and yardangs. **Mega-yardangs**, which are over 100 m long and up to 1,000 m wide, are reported only from the central Sahara and Egypt, some good examples occurring in the Boukou area near the Tibesti Mountains of Chad.

In the Qaidam Basin, Central Asia, eight forms of yardang occur: mesas, sawtooth crests, cones, pyramids, very long ridges, hogbacks, whalebacks, and low streamlined whalebacks (Halimov and Fezer 1989). Yardangs have been reported from Central Asia (the Taklimakan Desert, China), the Near East (the Lut Desert, southeastern Iran; the Khash Desert, Afghanistan; the Sinai Peninsula; and Saudi Arabia), several localities across the Saharan region, North America (the Mojave Desert, California), and South America (the Talara and Paracas–Ica regions, Peru). The yardangs in the Lut Basin, Iran, are among the largest on the planet. They stand up to 80 m tall and are carved out of the Lut Formation, which consists of fine-grained, horizontally bedded, silty clays and limey gypsum-bearing sands.

Plate 12.2 Floor of Rooipan, a small pan or deflation hollow in the south-west Kalahari. The pan accumulates limited rainfall (less than 150 mm per annum in this area) in the wet season, but receives additional moisture by groundwater seepage.
(*Photograph by Dave Thomas*)

Box 12.1

THE ORIGIN OF PANS

A uniquely aeolian origin for pans is disputable. Recent research indicates that a range of processes may lead to pan formation. Deflation may top the list, but excavation by animals and karst-type solution may play a role in some cases. Pan formation appears to run along the following lines (Goudie and Wells 1995). First, certain environmental conditions are prerequisites to pan formation. Low effective precipitation and sparse vegetation cover are the main necessary conditions, but salt accumulation helps as it curbs vegetation growth. Second, the local ground surface and sedimentary cover must be susceptible of erosion. Vulnerable materials include sands and sandstones, clays and shales, and marls. These materials are susceptible only where more than a thin layer of a resistant deposit such as calcrete does not cap them. Once an initial depression is created, several processes may assist its growth. Deflation is the chief process but it may be enhanced by animals' overgrazing and trampling the ground and by salt weathering, which may attack bedrock. A depression will not continue to grow unless it is protected from fluvial processes by being isolated from an effective and integrated fluvial system. Such protection may be afforded by low slope angles, episodic desiccation and dune encroachment, dolerite intrusions, and tectonic disturbance.

Yardangs are carved out of sediments by abrasion and deflation, although gully formation, mass movements, and salt weathering may also be involved. Yardang evolution appears to follow a series of steps (Halimov and Fezer 1989; Goudie 1999). First, suitable sediments (e.g. lake beds and swamp deposits) form under humid conditions. These sediments then dry out and are initially eaten into by the wind or by fluvial gullying. The resulting landscape consists of high ridges and mesas separated by narrow corridors that cut down towards the base of the sediments. Abrasion then widens the corridors and causes the ridge noses to retreat. At this stage, slopes become very steep and mass failures occur, particularly along desiccation and contraction cracks. The ridges are slowly converted into cones, pyramids, sawtooth forms, hogbacks, and whalebacks. Once the relief is reduced to less than 2 m, the whole surface is abraded to create a simple aerodynamic form – a low streamlined whaleback – which is eventually reduced to a plain surface.

Zeugen (singular *Zeuge*), also called **perched** or **mushroom rocks**, are related to yardangs (Plate 12.3). They are produced by the wind eating away strata, and especially soft strata close to the ground. Exceptionally, where sand-laden wind is funnelled by topography, even hard rocks may be fluted, grooved, pitted, and polished by sandblasting. An example comes from Windy Point, near Palm Springs, in the Mojave Desert, California.

Ventifacts

Cobbles and pebbles on stony desert surfaces often bear facets called **ventifacts**. The number of edges or keels they carry is sometimes connoted by the German terms *Einkanter* (one-sided), *Zweikanter* (two-sided), and *Dreikanter* (three-sided). The pyramid-shaped *Dreikanter* are particularly common. The abrasion of more than one side of a pebble or cobble does not necessarily mean more than one prevailing wind direction. Experimental studies have shown that ventifacts may form even when the wind has no preferred direction. And, even where the wind does tend to come from one direction, a ventifact may be realigned by dislodgement.

The mechanisms by which ventifacts form are debatable, despite over a century of investigation (see Livingstone and Warren 1996, pp. 30–2), but abrasion by dust and silt, rather than by blasting by sand, is probably the chief cause. Interestingly, the best-developed ventifacts come from polar and periglacial regions, where, owing partly to the higher density of the air and partly

Plate 12.3 Zeugen, Farafra, Western Desert, Egypt. The limestone pillars are undercut by sand-blasting. (*Photograph by Tony Waltham Geophotos*)

to the higher wind speeds, larger particles are carried by the wind than in other environments.

AEOLIAN DEPOSITIONAL FORMS

Sand accumulations come in a range of sizes and forms. Deposition may occur as **sheets of sand** (dune fields and sand seas) or **loess** or as characteristic **dunes**. It is a popular misconception that the world's deserts are vast seas of sand. Sandy desert (or *erg*) covers just 25 per cent of the Sahara, and little more than a quarter of the world's deserts. Smaller sand accumulations and dune fields are found in almost all the world's arid and semi-arid regions.

Sand accumulations, in sand seas and in smaller features, usually evolve bedforms. They are called bedforms because they are produced on the 'bed' of the atmosphere as a result of fluid movement – airflow. They often develop regular and repeating patterns in response to the shearing force of the wind interacting with the sediment on the ground surface. The wind moulds the sediment into various landforms. In turn, the landforms modify the airflow. A kind of equilibrium may become established between the airflow and the evolving landforms, but it is readily disrupted by changes in sand supply, wind direction, wind speed, and, where present, vegetation.

Dune formation

Traditionally, geomorphologists studied dune form and the texture of dune sediments. Since around 1980, emphasis has shifted to investigations of sediment transport and deposition and of their connection to dune inception, growth, and maintenance. Research has involved field work and wind-tunnel experiments, as well as mathematical models that simulate dune formation and development (see Nickling and McKenna Neuman 1999). Nonetheless, it is still not fully clear how wind, blowing freely over a desert plain, fashions dunes out of sand. The interactions between the plain and the flow of sand in which regular turbulent patterns are set up are probably the key. Plainly, it is essential that wind velocity is reduced to allow grains to fall out of the conveying wind. Airflow rates are much reduced in the lee of obstacles and in hollows. In addition, subtle influences of surface roughness, caused by grain size differences, can induce aerodynamic effects that encourage deposition. Deposition may produce a sand patch. Once a sand patch is established, it may grow into a dune by trapping saltating grains, which are unable to rebound on impact as easily as they are on the surrounding stony surface. This mechanism works only if the sand body is broader than the flight lengths of saltating grains. A critical lower width of 1–5 m seems to represent the limiting size for dunes. On the leeside of the dune, airflow separates and decelerates. This change enhances sand accumulation and reduces sand erosion, so the dune increases in size. The grains tend to be trapped on the slip face, a process aided by wind compression and consequent acceleration over the windward slope. The accelerated airflow erodes the windward slope and deposits the sand on the lee slope. As the sand patch grows it becomes a dune. Eventually, a balance is reached between the angle of the windward slope, the dune height, the level of airflow acceleration, and so the amount of erosion and deposition on the windward and lee slopes. The dune may move downwind (Figure 12.3).

Figure 12.4 is a speculative model of the conditions conducive to the formation of different dune types, which are discussed below (Livingstone and Warren 1996, 80). The two axes represent the two main factors controlling dune type. The first represents an unspecified measure of the amount of sand available for dune formation, while the second axis represents the variability of wind direction.

Dune types

Some researchers believe that aeolian bedforms form a three-tiered hierarchy. Nicholas Lancaster (1995) identified three superimposed bedforms, the first two of which occur in all sand seas: (1) wind ripples; (2) individual simple dunes or superimposed dunes on compound and complex dunes; and (3) compound and complex dunes or draa.

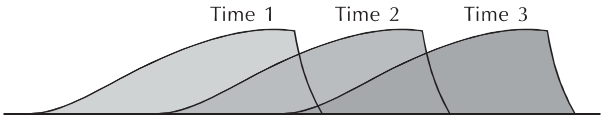

Figure 12.3 The downwind progress of a transverse dune.
Source: Adapted from Livingstone and Warren (1996, 73)

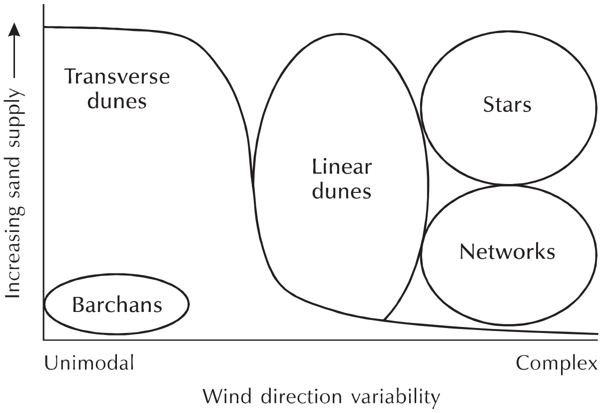

Figure 12.4 Dune types in relation to the variability of wind direction and sand supply.
Source: Adapted from Livingstone and Warren (1996, 80)

Ripples

Wind ripples are the smallest aeolian bedform. They are regular, wave-like undulations lying at right-angles to the prevailing wind direction. The size of ripples increases with increasing particle size, but they typically range from about 10 to 300 mm high and are typically spaced a few centimetres to tens of metres apart (Colour Plate 15, inserted between pages 208 and 209; Plate 12.4). Wind ripples develop in minutes to hours and quickly change if wind direction or wind speed alters.

Seemingly simple aeolian bedforms, ripples have withstood attempts to explain them. Several hypotheses have been forthcoming, but most are flawed (see Livingstone and Warren 1996, 27). According to what is perhaps the most plausible model (Anderson 1987; Anderson and Bunas 1993), ripple initiation requires an irregularity in the bed that perturbs the population of reptating grains. By simulating the process, repeated ripples occurred after about 5,000 saltation impacts with a realistic wavelength of about six mean reptation wavelengths. In a later version of the model (Anderson and Bunas 1993), two grain sizes were included. Again, ripples developed and these bore coarser particles at their crests, as is ordinarily the case in actual ripples.

Plate 12.4 Mega-ripples formed on a hard sebkha surface in the United Arab Emirates. (*Photograph by Dave Thomas*)

Free dunes

Dunes are collections of loose sand built piecemeal by the wind (Figure 12.5). They usually range from a few metres across and a few centimetres high to 2 km across and 400 m high. Typical sizes are 5–30 m high and spaced at 50–500-m intervals. The largest dunes are called **draa** or **mega-dunes** and may stand 400 m high and sit more than 500 m apart, with some displaying a spacing of up to 4 km.

Dunes may occur singly or in dune fields. They may be active or else fixed by vegetation. And they may be free dunes or dunes anchored in the lee of an obstacle (impeded dunes). The form of free dunes is determined largely by wind characteristics, while the form of anchored dunes is strongly influenced by vegetation, topography, or highly local sediment sources. Classifications of dune forms are many and varied, with local names often being used to describe the same forms. A recent classification is based upon dune formation and identifies two primary forms – free and anchored – with secondary forms being established according to morphology or orientation, in the case of free dunes, and vegetation and topography, in the case of anchored dunes (Livingstone and Warren 1996, 75) (Table 12.3).

Free dunes may be classed according to orientation (transverse) or form (linear, star, and sheet) (Figure 12.6). All types of **transverse dune** cover about 40 per cent of active and stabilized sand seas. The transverse variety (Table 12.3) is produced by unidirectional winds and forms asymmetric ridges that look like a series of barchan dunes whose horns are joined, with their slip faces all facing roughly in the same direction. **Barchans** are isolated forms that are some 0.5–100 m high and 30–300 m wide (Plate 12.5). They rest on firm desert surfaces, such as stone pavements, and move in the direction of the horns, sometimes as much as 40 m/yr. They form under conditions of limited sand supply and unidirectional winds. Other transverse dune types are domes and reversing dunes. **Domes** lack slip faces but have an orientation and pattern of sand transport allied to transverse dunes. **Reversing dunes**, which have slip faces on opposite sides of the crest that form in response to wind coming from two opposing directions, are included in the transverse class because net sand transport runs at right-angles to the crest.

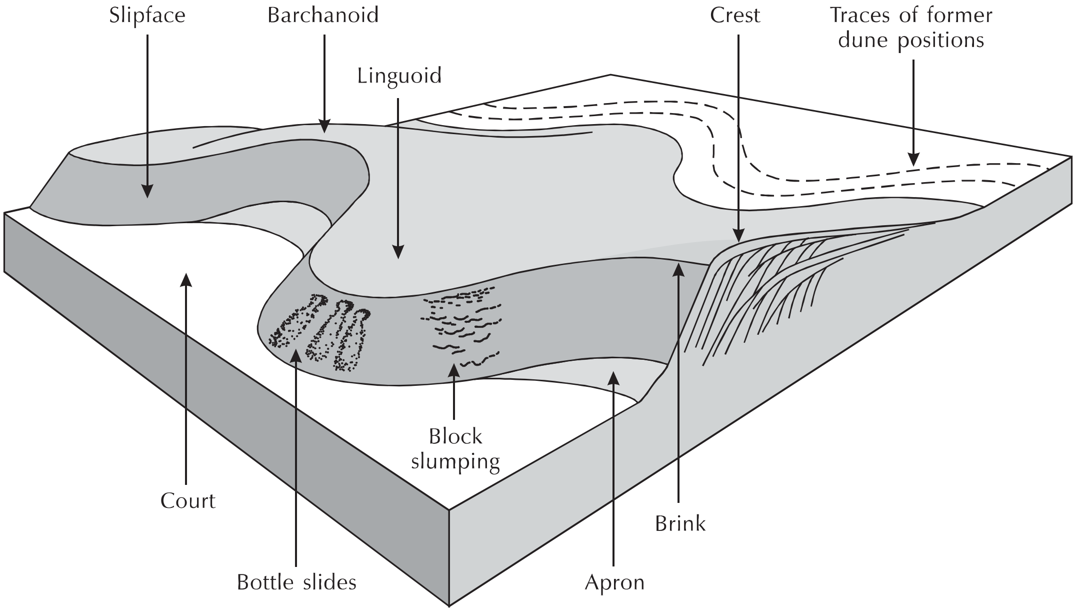

Figure 12.5 The main features of a dune.
Source: Adapted from Livingstone and Warren (1996, 65)

Linear dunes have slip faces on either side of a crest line, but only one of them is active at any time, and sand transport runs parallel to the crest. They may be divided into sharp-crested *seifs*, also called *siefs* and *sayfs* (Plate 12.6), and more rounded sand ridges. Both are accumulating forms that either trap downwind sand from two directions or lie parallel to the dominant wind. Linear dunes occur in all the world's major sandy deserts. They stand from less than a couple of metres high to around a couple of hundred metres high and may extend for tens of kilometres. They often run parallel but many meander with varied spacing and may join at 'Y' or 'tuning fork' junctions.

Dune networks and **star dunes** possess a confused set of slip faces that point in several directions. Dune networks, which are very widespread, usually occur in a continuous sand cover. They are composed of dunes no more than a few metres high and spaced 100 m or so apart. Stars dunes bear several arms that radiate from a central peak (Plate 12.7). They may be up to 400 m high and spaced between about 150 and at least 5,000 m. Found in many of the world's major sand seas, star dunes cover a large area only in the Great Eastern sand sea of Algeria.

Sheets of sand come in two varieties – zibars and streaks. **Zibars** are coarse-grained bedforms of low relief with no slip faces. Their surfaces consist exclusively of wind ripples and local shadow and shrub-coppice dunes. They are common on sand sheets and upwind of sand seas. **Streaks**, also called **sand sheets** or **stringers**, are large bodies of sand that bear no obvious dune forms. They occupy larger areas of sand seas than accumulations with dunes.

Anchored dunes

Several types of dune are controlled by vegetation, topography, or local sediment sources. These **anchored** or **impeded dunes** come in a variety of forms (Table 12.3; Figure 12.7). Topographic features cause several distinct types of anchored dune. **Lee dunes** and **foredunes** are connected to the pattern of airflow around obstacles. Wind-tunnel experiments have shown that the growth of **climbing dunes** (Plate 12.8) and **echo dunes** depends

Table 12.3 A classification of dunes

Primary dune forms	*Criteria for subdivision*	*Secondary dune forms*	*Description*
Free	*Morphology or orientation:*		
	Transverse	Transverse	Asymmetric ridge
		Barchan	Crescentic form
		Dome	Circular or elliptical mound
		Reversing	Asymmetric ridge with slip faces on either side of the crest
	Linear	Seif	Sharp-crested ridge
		Sand ridge	Rounded, symmetric ridge, straight or sinuous
	Star	Star	Central peak with three or more arms
		Network	Confused collection of individual dunes whose slip faces have no preferred orientation
	(Sheets)	Zibar	Coarse-grained bedform of low relief and possessing no slip face
		Streaks or stringers or sand sheets	Large bodies of sand with no discernible dune forms
Anchored	*Vegetation and topography:*		
	Topography	Echo	Elongated ridge lying roughly parallel to, and separated from, the windward side of a topographic obstacle
		Climbing dune or sand ramp	Irregular accumulation going up the windward side of a topographic obstacle
		Cliff-top	Dune sitting atop a scarp
		Falling	Irregular accumulation going down the leeward side of a large topographic obstacle
		Lee	Elongated downwind from a topographic obstacle
		Fore	Roughly arcuate with arms extending downwind around either side of a topographic obstacle
		Lunette	Crescent-shaped opening upwind
	Vegetation	Vegetated sand mounds	Roughly elliptical to irregular in plan, streamlined downwind
		Parabolic	U-shaped or V-shaped in plan with arms opening upwind
		Coastal	Dunes formed behind a beach
		Blowout	Circular rim around a depression

Source: Based on Livingstone and Warren (1996, 74–101)

upon the slope of the obstacle. When the upwind slope of an obstacle is less than around 30°, sand blows over it. When it is above 30°, then sand is trapped and a climbing dune or sand ramp forms. If it exceeds 50°, then an echo dune forms at an upwind distance of some thrice the height of the obstacle. **Cliff-top dunes** may form in the zone of slightly lower wind velocity just beyond the crest of an obstacle. **Falling dunes** form in the lee of an obstacle, where the air is calmer. If the obstacle is narrow, then sand moving around the edges may form lee dunes that extend downwind. **Lunettes** are crescent-shaped dunes that open upwind and are associated with pans (p. 299).

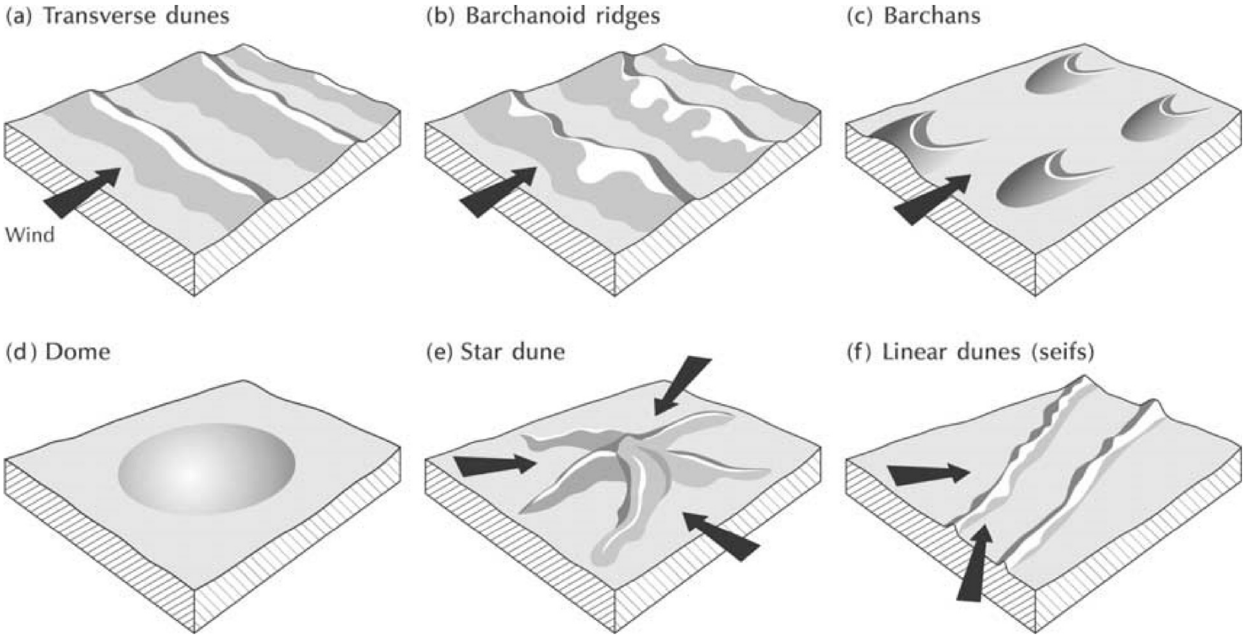

Figure 12.6 Types of free dunes.
Source: Adapted from McKee (1979)

Plate 12.5 A barchan dune in the United Arab Emirates. The dune is a mobile form that is migrating over a hard, clay-rich surface.
(*Photograph by Dave Thomas*)

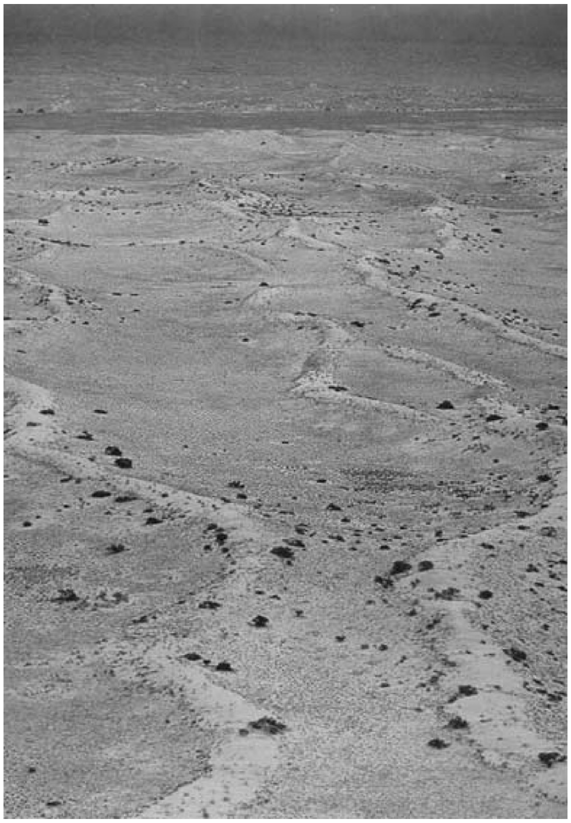

Plate 12.6 Partially vegetated and sinuous linear dunes in the south-west Kalahari.
(*Photograph by Dave Thomas*)

Plate 12.7 A large star dune, over 200 m high, near Sossus Vlei in the Namib Desert.
(*Photograph by Dave Thomas*)

Plants may act as foci for dune formation, and three types of dune are associated with vegetation. The commonest type of plant-anchored dune is **vegetated sand mounds**, also known as *nabkha*, *nebkha*, shrub dunes, or hummock dunes (Plate 12.9). These form around a bush or clump of grass, which acts as an obstacle for sand entrapment. **Parabolic dunes**, or **'hairpin' dunes**, are U-shaped or V-shaped in plan with their arms opening upwind. They are common in vegetated desert margins. In the Thar Desert, India, they may attain heights of many tens of metres. They are also found in cold climates, as in Canada and the central USA, and at coastal sites. As to their formation, it is generally thought that parabolic dunes grow from blowouts. **Blowouts** are depressions created by the deflation of loose sand partly bound by plant roots. They are bare hollows within vegetated dunes and are very common in coastal dunes and in stabilized (vegetated) dunes around desert margins.

Dunefields and sand seas

Dunefields are accumulations of sand, occupying areas of less than 30,000 km^2 with at least ten individual dunes spaced at distances exceeding the dune wavelength (Cooke *et al.* 1993, 403). They contain relatively small and simple dunes. They may occur anywhere that loose sand is blown by the wind, even at high latitudes, and there are thousands of them. In North America, dunefields occur in the south-western region, and in intermontane basins such as Kelso and Death Valley, California.

Sand seas differ from dunefields in covering areas exceeding 30,000 km^2 and in bearing more complex and bigger dunes. In both sand seas and dunefields, ridges or mounds of sand may be repeated in rows, giving the surface a wavy appearance. About 60 per cent of sand seas are dune-covered, while others may be dune-free and comprise low sand sheets, often with some vegetation cover. Sand seas have several local names: ergs in the northern Sahara, *edeyen* in Libya, *qoz* in the Sahara, *koum* or

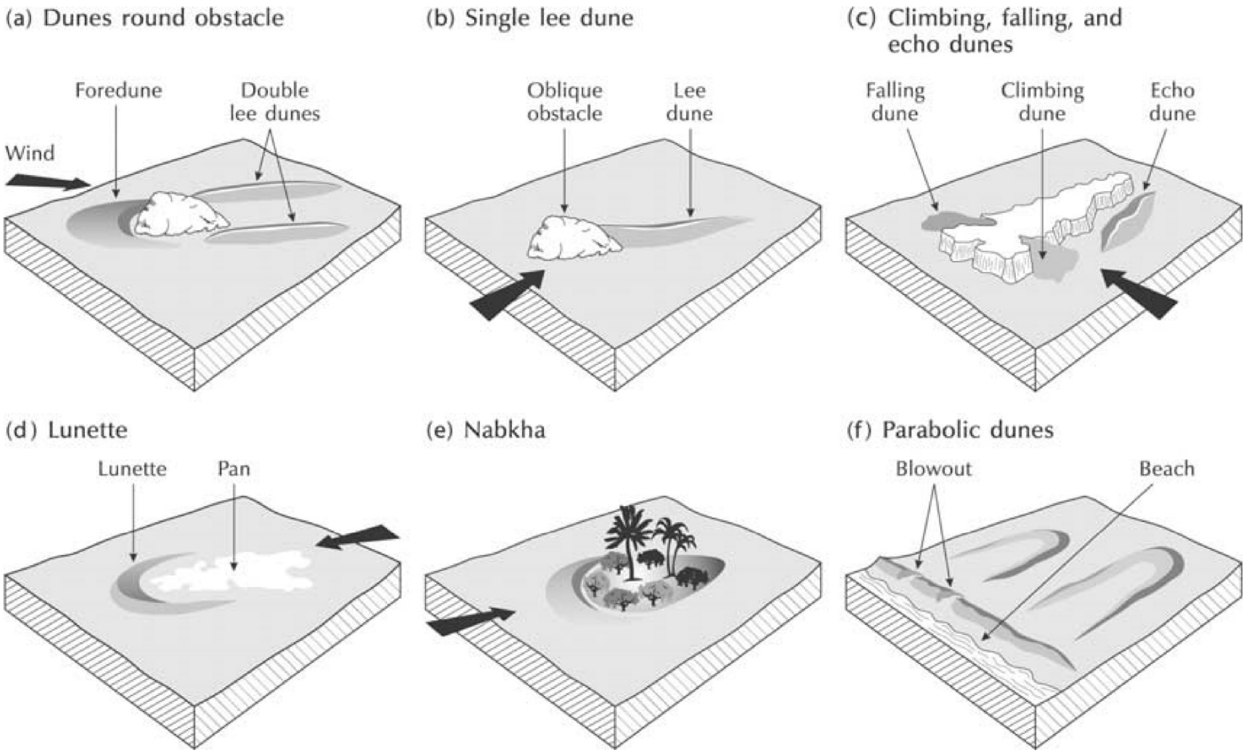

Figure 12.7 Types of anchored dunes.
Source: Partly adapted from Livingstone and Warren (1996, 88)

Plate 12.8 Small climbing dunes in the Mohave Desert, western USA.
(*Photograph by Dave Thomas*)

Plate 12.9 Nebkha dunes formed from gypsum-rich sands in central Tunisia. Note that the palm trees in the background are growing on an artesian spring mound.
(*Photograph by Dave Thomas*)

kum and *peski* in Central Asia, and *nafud* or *nefud* in Arabia. They are regional accumulations of windblown sand with complex ancestry that are typically dominated by very large dunes (at least 500 m long or wide or both) of compound or complex form with transverse or pyramidal shapes (Figure 12.8). They also include accumulations of playa and lake deposits between the dunes and areas of fluvial, lake, and marine sediments. Sand seas are confined to areas where annual rainfall is less than 150 mm within two latitudinal belts, one 20°–40° N and the other 20°–40° S. The largest sand sea is the Rub' al Khali (the 'Empty Quarter') in Saudi Arabia, which is part of a 770,000-km^2 area of continuous dunes. About fifty comparable, if somewhat less extensive, sand seas occur in North and southern Africa, Central and Western Asia, and central Australia. In South America, the Andes constrain the size of sand seas, but they occur in coastal Peru and north-western Argentina and contain very large dunes. In North America, the only active sand sea is in the Gran Desierto of northern Sonora, northern Mexico, which extends northwards into the Yuma Desert of Arizona and the Algodones Dunes of south-eastern California. The Nebraska Sand Hills are a sand sea that has been fixed by vegetation. A single sand sea may store vast quantities of sand. The Erg Oriental, with an area of 192,000 km^2 and average thickness of 26 m, houses 4,992 km^3 of sand. The Namib Sand Sea is more modest, storing 680 km^3 of sand (Lancaster 1999). Sand seas that have accumulated in subsiding basins may be at least 1,000 m thick, but others, such as the ergs of linear dunes in the Simpson and Great Sandy Deserts of Australia, are as thick as the individual dunes that lie on the alluvial plains.

Dunefields and sand seas occur largely in regions lying downwind of plentiful sources of dry, loose sand, such as dry river beds and deltas, floodplains, glacial outwash plains, dry lakes, and beaches. Almost all major ergs are located downwind from abandoned river courses in dry areas lacking vegetation that are prone to persistent wind erosion. Most of the Sahara sand supply, for instance, probably comes from alluvial, fluvial, and lacustrine systems fed by sediments originating from the Central African uplands, which are built of Neogene beds. The sediments come directly from deflation of alluvial sediments and, in the cases of the Namib, Gran Desierto, Sinai, Atacama, and Arabian sand seas, indirectly from coastal sediments. Conventional wisdom holds that sand from these voluminous sources moves downwind and piles up as very large dunes in places where its transport is curtailed by topographic barriers that disrupt airflow

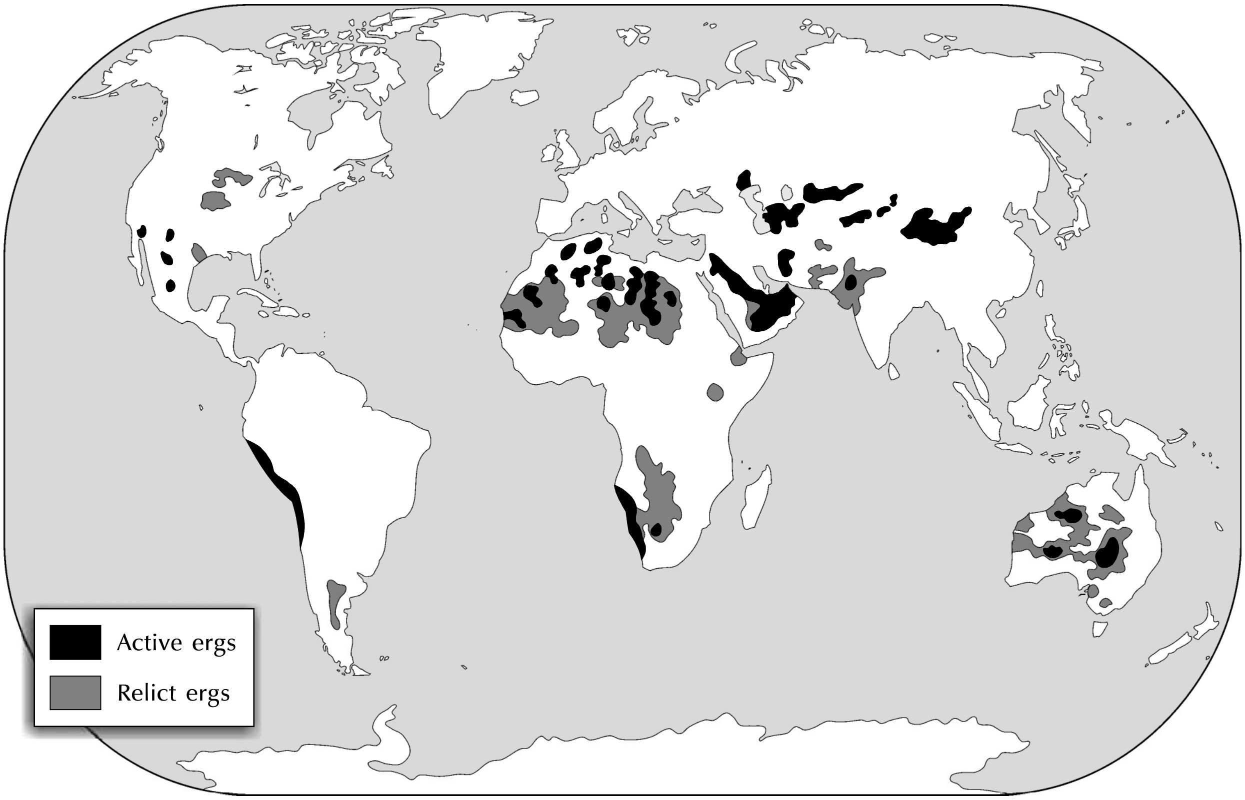

Figure 12.8 World distribution of active and relict ergs.
Sources: Adapted from Sarnthein (1978) and Wells (1989)

or by airflow being forced to converge. By this process, whole ergs and dunefields may migrate downwind for hundreds of kilometres from their sand sources.

Loess

Loess is a terrestrial sediment composed largely of windblown silt particles made of quartz. It covers some 5–10 per cent of the Earth's land surface, much of it forming a blanket over pre-existing topography that may be up to 400 m thick (Figure 12.9; Plate 12.10). Loess is easily eroded by running water and possesses underground pipe systems, pseudo-karst features, and gullies. In areas of high relief, landslides are a hazard.

To form, loess requires three things: (1) a source of silt; (2) wind to transport the silt; and (3) a suitable site for deposition and accumulation (Pye and Sherwin 1999). In the 1960s, it was thought that glacial grinding of rocks provided the quartz-dominated silt needed for loess formation. It is now known that several other processes produce silt-sized particles – comminution by rivers, abrasion by wind, frost weathering, salt weathering, and chemical weathering. However produced, medium and coarse silt is transported near the ground surface in short-term suspension and by saltation. Vegetation, topographic obstacles, and water bodies easily trap materials of this size. Fine silt may be borne further and be brought down by wet or dry deposition. This is why loess becomes thinner and finer-grained away from the dust source. To accumulate, dust must be deposited on rough surfaces because deposits on a dry and smooth surface are vulnerable to resuspension by wind or impacting particles. Vegetation surfaces encourage loess accumulation. Even so, for a 'typical' loess deposit to form, the dust must accumulate at more than 0.5 mm/year, which is equivalent to a mass accumulation

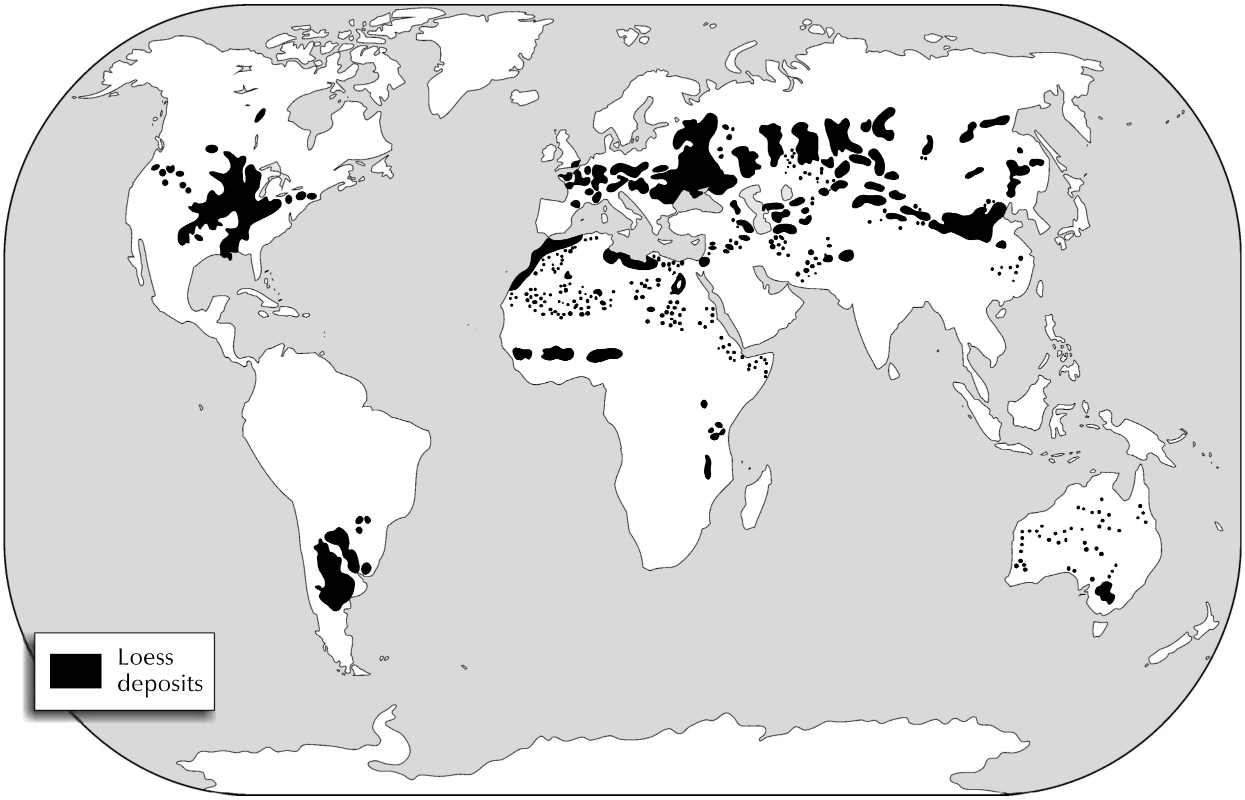

Figure 12.9 World distribution of loess.
Source: Adapted from Livingstone and Warren (1996, 58)

Plate 12.10 Section through a ~15-m-thick loess exposure on the Columbia Plateau in Washington State, USA. (*Photograph by Kate Holden*)

of 625 g/m^2/yr. A lower rate of deposition will lead to dilution by weathering, by mixing by burrowing animals, by mixing with other sediments, and by colluvial reworking. During the late Pleistocene in North America and Western Europe, loess accumulated at more than 2 mm/yr, equivalent to 2,600 g/m^2/yr.

HUMANS AND AEOLIAN LANDSCAPES

Wind erosion may bring about long-term impacts on humans and human activities. It may damage agricultural and recreational lands, and, on occasions, impair human health. As Livingstone and Warren (1996, 144) put it:

> There has been and continues to be massive investment across the world in the control of aeolian geomorphological processes. It has happened in Saharan and Arabian oases for thousands of years; on the Dutch coast since the fourteenth century; on the Danish sandlands particularly in the eighteenth and nineteenth centuries; in the Landes of south-western France from the nineteenth century; in the United States since the Dust Bowl of the 1930s; on the Israeli coast since shortly after the creation of the State in the late 1940s; on the Russian and central Asian steppes since the Stalinist period; since the 1950s in the oil-rich desert countries of the Middle East; since the early 1970s in the Sahel, North Africa, India and China; and less intensively but significantly in other places. In most of these situations, applied aeolian geomorphology won huge resources and prestige.

The chief problems are the erosion of agricultural soils, the raising of dust storms, and the activation of sand dunes, all of which may result from human disturbance, overgrazing, drought, deflated areas, and the emissions of alkali-rich dust (see Livingstone and Warren 1996, 144–71).

Cases of wind erosion

The **Dust Bowl** of the 1930s is the classic example of wind erosion (Box 12.2). Even greater soil-erosion events occurred in the Eurasian steppes in the 1950s and 1960s. On a smaller scale, loss of soil by wind erosion in Britain, locally called blowing, is a worse problem than erosion by water. The light sandy soils of East Anglia, Lincolnshire, and east Yorkshire, and the light peats of the Fens are the most susceptible. **Blows** can remove up to 2 cm of topsoil containing seeds, damage crops by sandblasting them, and block ditches and roads. Blowing is recorded as long ago as the thirteenth century, but the problem worsened during the 1960s, probably owing to a change in agricultural practices. Inorganic fertilizers replaced farmyard manure, heavy machinery was brought in to cultivate and harvest some crops, and hedgerows were grubbed to make fields better-suited to mechanized farming. Intensively cultivated areas with light soils in Europe are generally prone to wind erosion and the subject of the European Union research project on **Wind Erosion and European Light Soils (WEELS)** (e.g. Riksen and De Graaff 2001). This international project began in 1998 and looked at sites in England, Sweden, Germany, and the Netherlands where serious wind-erosion problems occur. The damage recorded depended very much on landscape factors and land-use. Most on-site damage, mainly in the form of crop losses and the cost of reseeding, occurred in sugar beet, oilseed rape, potato, and maize fields. In the cases of sugar beet and oilseed rape, the costs may be as much as €500 per hectare every five years, although farmers are fully aware of the risk of wind erosion and take preventive measures. In Sweden, measures taken to reduce wind erosivity include smaller fields, autumn sowing, rows planted on wind direction, mixed cropping, and shelterbelts. And measures taken to reduce soil erodibility include minimum tillage, manuring, applying rubber emulsion, watering the soil, and pressing furrows.

Modelling wind erosion

Researchers have devised empirical models, similar in form to the Universal Soil Loss Equation (p. 179), to predict the potential amount of wind erosion under given conditions and to serve as guide to the management practices needed to control the erosion. The **Wind Erosion Equation (WEQ)**, originally developed by William S. Chepil, takes the form:

$$E = f(I, C, K, L, V)$$

where E is the soil loss by wind, I is the erodibility of the soil (vulnerability to wind erosion), C is a factor representing local wind conditions, K is the soil surface roughness, L is the width of the field in the direction of

Box 12.2

THE DUST BOWL

The natural vegetation of the Southern Great Plains of Colorado, Kansas, New Mexico, Oklahoma, and Texas is prairie grassland which is adapted to low rainfall and occasional severe droughts. During the 'Dirty Thirties', North American settlers arrived from the east. Being accustomed to more rainfall, they ploughed up the prairie and planted wheat. Wet years saw good harvests; dry years, which were common during the 1930s, brought crop failures and dust storms. In 1934 and 1935, conditions were atrocious. Livestock died from eating excessive amounts of sand, human sickness increased because of the dust-laden air. Machinery was ruined, cars were damaged, and some roads became impassable. The starkness of the conditions is evoked in a report of the time:

> The conditions around innumerable farmsteads are pathetic. A common farm scene is one with high drifts filling yards, banked high against buildings, and partly or wholly covering farm machinery, wood piles, tanks, troughs, shrubs, and young trees. In the fields near by may be seen the stretches of hard, bare, unproductive subsoil and sand drifts piled along fence rows, across farm roads, and around Russian-thistles and other plants. The effects of the black blizzards [massive dust storms that blotted out the Sun and turned day into night] are generally similar to those of snow blizzards. The scenes are dismal to the passerby; to the resident they are demoralizing.
>
> (Joel 1937, 2)

The results were the abandonment of farms and an exodus of families, remedied only when the prairies affected were put back under grass. The effects of the dust storms were not always localized:

> On 9 May [1934], brown earth from Montana and Wyoming swirled up from the ground, was captured by extremely high-level winds, and was blown eastward toward the Dakotas. More dirt was sucked into the airstream, until 350 million tons were riding toward urban America. By late afternoon the storm had reached Dubuque and Madison, and by evening 12 million tons of dust were falling like snow over Chicago – 4 pounds for each person in the city. Midday at Buffalo on 10 May was darkened by dust, and the advancing gloom stretched south from there over several states, moving as fast as 100 miles an hour. The dawn of 11 May found the dust settling over Boston, New York, Washington, and Atlanta, and then the storm moved out to sea. Savannah's skies were hazy all day 12 May; it was the last city to report dust conditions. But there were still ships in the Atlantic, some of them 300 miles off the coast, that found dust on their decks during the next day or two.
>
> (Worster 1979, 13–14)

the prevailing wind, and V is a measure of the vegetation cover. Although this equation is similar to the ULSE, its components cannot be multiplied together to find the result. Instead, graphical, tabular, or computer solutions are required. Originally designed to predict wind erosion in the Great Plains, the WEQ has been applied to other regions in the USA, especially by the Natural Resources Conservation Service (NRCS). However, the WEQ suffered from several drawbacks. It was calibrated for conditions in eastern Kansas, where the climate is rather dry; it was only slowly adapted to tackle year-round changes in crops and soils; it was unable to cope with the complex interplay between crops, weather, soil, and erosion; and it over-generalized wind characteristics.

Advances in computing facilities and databases have prompted the development of a more refined **Wind Erosion Prediction System** (**WEPS**), which is designed to replace WEQ. This computer-based model simulates the spatial and temporal variability of field conditions and soil erosion and deposition within fields of varying shapes and edge types and complex topographies. It does so by using the basic processes of wind erosion and the processes that influence the erodibility of the soil. Another **Revised Wind Erosion Equation** (**RWEQ**) has been used in conjunction with GIS databases to scale up the field-scale model to a regional model (Zobeck *et al.* 2000). An **integrated wind-erosion modelling system**, built in Australia, combines a physically based wind-erosion scheme, a high-resolution atmospheric model, a dust-transport model, and a GIS database (Lu and Shao 2001). The system predicts the pattern and intensity of wind erosion, and especially dust emissions from the soil surface and dust concentrations in the atmosphere. It can also be used to predict individual dust-storm events.

SUMMARY

Several landforms are products of wind erosion. Examples are lag deposits and stone pavements, deflation hollows and pans, yardangs and *Zeugen*, and ventifacts. Sand accumulations range in size from ripples, through dunes, to dunefields and sand seas. Dunes may be grouped into free and anchored types. Free dunes include transverse dunes, seifs, star dunes, and zibars. Anchored dunes form with the help of topography or vegetation. They include echo dunes, falling dunes, parabolic dunes, and coastal dunes. Dunefields and sand seas are collections of individual dunes. The largest sand sea – the Rub' al Khali of Saudi Arabia – occupies 770,000 km^2. Loess is an accumulation of windblown silt particles and covers about 5–10 per cent of the land surface. Wind erosion can often be a self-inflicted hazard to humans, damaging agricultural and recreational land and harming human health. Several models predict wind erosion at field and regional scales, the latest examples combining physical processes with GIS databases and atmospheric models.

ESSAY QUESTIONS

1 How does wind shape landforms?

2 How do sand dunes form?

3 Discuss the problems and remedies of soil erosion by wind.

FURTHER READING

Cooke, R. U., Warren, A., and Goudie, A. S. (1993) *Desert Geomorphology*. London: UCL Press.
Comprehensive and clear account of form and process in arid and semi-arid environments.

Goudie, A. S., Livingstone, I., and Stokes, S. (eds) (1999) *Aeolian Environments, Sediments and Landforms*. Chichester: John Wiley & Sons.
Perhaps a little heavy for the neophyte, but full of excellent papers.

Lancaster, N. (1995) *Geomorphology of Desert Dunes*. London: Routledge.
If you are interested in sand dunes, then look no further.

Livingstone, I. and Warren, A. (1996) *Aeolian Geomorphology: An Introduction*. Harlow, Essex: Longman.
The best introduction to the subject. A must for the serious student.

Thomas, D. S. G. (ed.) (1997) *Arid Zone Geomorphology: Process, Form and Change in Drylands*, 2nd edn. Chichester: John Wiley & Sons.
An excellent collection of essays that is full of interesting ideas and examples.