Section 10.1 Activities

1. Explain the term *rainfall variability*.
2. Compare and contrast the seasonal and monthly temperature ranges for Casablanca and Timbuktu.
3. Using the geographical locations of Casablanca and Timbuktu, suggest reasons for the differences you have noted in their seasonal and monthly temperature ranges.
4. Compare and contrast the precipitation totals for Cairo, Casablanca and Timbuktu. Suggest reasons for the differences you have identified.

10.2 Landforms of hot arid and semi-arid environments

Weathering processes

Weathering in deserts is superficial and highly selective. The traditional view was that all weathering in deserts was mechanical due to the relative absence of water. However, it is increasingly realised that chemical weathering is important, and that water is important for mechanical weathering, especially exfoliation. Weathering is greatest in shady sites and in areas within reach of soil moisture. Chemical weathering is enhanced in areas that experience dew or coastal fog. As rainfall increases, weathering increases; and soils tend to have more clay, less salt and more distinct horizons. Salt weathering is frequent in arid areas because desert rocks often have soluble salts, and these salts can disintegrate rocks through salt crystal growth and hydration.

Salt crystallisation causes the decomposition of rock by solutions of salt (Figure 10.4). There are two main types of salt crystal growth. First, in areas where temperatures fluctuate around 26–28 °C, sodium sulphate (Na_2SO_4) and sodium carbonate (Na_2CO_3) expand by about 300 per cent. This creates pressure on joints, forcing them to crack. Second, when water evaporates, salt crystals may be left behind. As the temperature rises, the salts expand and exert pressure on rock. Both mechanisms are frequent in hot desert regions where low rainfall and high temperatures cause salts to accumulate just below the surface.

Experiments investigating the effectiveness of saturated salt solutions have shown a number of results:

- The most effective salts are sodium sulphate, magnesium sulphate and calcium chloride.
- The rate of disintegration of rocks is closely related to porosity and permeability.

Figure 10.4 Salt crystallisation

- Surface texture and grain size control the rate of rock breakdown. This diminishes with time for fine materials and increases over time for coarse materials.
- Salt crystallisation is more effective than insolation weathering, hydration or freeze–thaw. However, a combination of freeze–thaw and salt crystallisation produces the highest rates of breakdown.

The most effective salts are, in descending order, sodium sulphate (Na_2SO_4), magnesium sulphate ($MgSO_4$) and calcium chloride ($CaCl_3$). Sodium sulphate caused a 100 gramme block of stone to break down to about 30 grammes – a loss of 70 per cent (Figure 10.5). Similarly, magnesium sulphate reduced a 95 gramme block to just over 40 grammes, a loss of over 50 per cent. The least effective salts were common salt (NaCl) and sodium carbonate (Na_2CO_3).

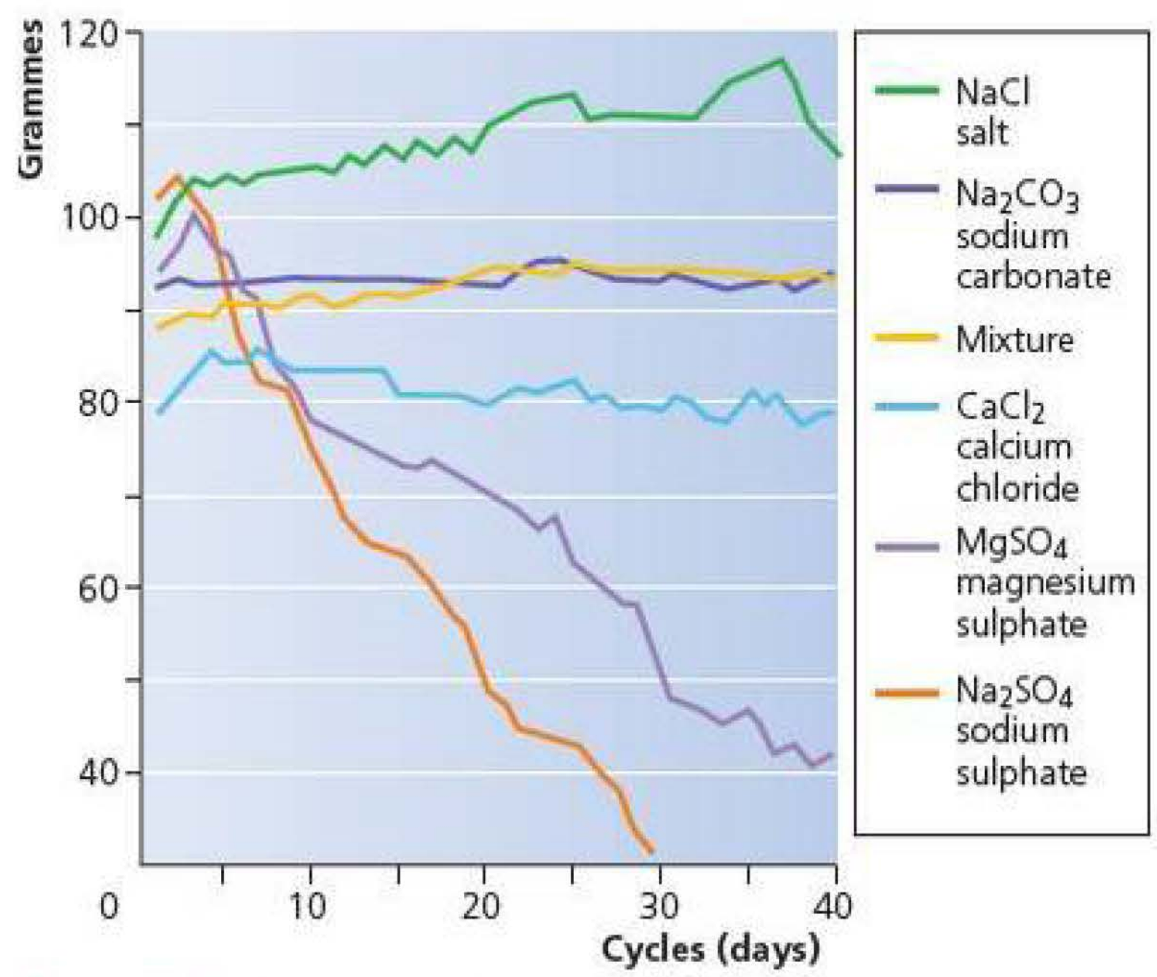


Figure 10.5 The effects of common salts on sandstone under laboratory conditions

Thermal fracturing refers to the break-up of rock as a result of repeated changes in temperature over a prolonged period of time. Disintegration or insolation weathering is found in hot desert areas where there is a large diurnal temperature range. In many desert areas, daytime temperatures exceed 40 °C, whereas night-time temperatures are little above freezing. Rocks heat up by day and contract by night. As rock is a poor conductor of heat, stresses occur only in the outer layers. This causes peeling or exfoliation to occur. Griggs (1936) showed that moisture is essential for this to happen. In the absence of moisture, temperature change alone did not cause the rocks to break down. The role of salt in insolation weathering has also been studied. The expansion of many salts such as sodium, calcium, potassium and magnesium has been linked with exfoliation. However, some geographers find little evidence to support this view.

In some instances, rocks may be split in two. Block disintegration is most likely to result from repeated heating and cooling. Such rocks are known as *kernsprung*. A more localised effect is granular disintegration. This occurs due to certain grains being more prone to expansion and contraction than others – this exerts great pressure on the grains surrounding them and forces them to break off.

Hydration is the process whereby certain minerals absorb water, expand and change. For example, gypsum is changed to anhydrate. Although it is often classified as a type of chemical weathering, mechanical stresses occur as well. When anhydrite ($CaSO_4$) absorbs water to become gypsum ($CaSO_4.2H_2O$), it expands by about 0.5 per cent. More extreme is the increase in volume of up to 1600 per cent by shales and mudstones when clay minerals absorb water.

Freeze–thaw occurs when water in joints and cracks freezes at 0 °C. It expands by about 10 per cent and exerts pressure up to a maximum of 2100 kg/cm² at –22 °C. This greatly exceeds most rocks' resistance. However, the average pressure reached in freeze–thaw is only 14 kg/cm².

Freeze–thaw is most effective in environments where moisture is plentiful and there are frequent fluctuations above and below freezing point. It can occur in deserts at high altitude and in continental interiors in winter.

Processes of erosion, transport and deposition by wind

The importance of wind in deserts has been hotly debated by geographers. At the end of the nineteenth century, it was considered to be a very effective agent in the formation of desert landforms. By contrast, in the twentieth century the role of wind was played down, in part because much of the research into deserts took place in high-relief, tectonically active areas such as the south-west USA. It was argued that:

- wind-eroded landscapes were only superficially eroded
- some features, such as playas, were formed by other processes, especially tectonic ones
- desert surfaces were protected from the wind by crusts, salts and gravel
- wind erosion depends on the availability of abrasive sands and only operates over a limited height range
- water is still very active.

However, in the middle of the twentieth century the use of aerial photography and satellites showed major features aligned with prevailing wind systems, such as yardangs in the Sahara, Iran, Peru and Arabia. In addition, examination of desert playas, which are large and frequent, showed that some are tectonic but others are aeolian. Dunes on the lee side of playas suggest that the dunes were deposited by excavating winds. In the Qattara Depression in the Sahara, 3335 km³ of material has been removed by the wind. Moreover, meteorological observations of dust storms have illustrated the importance of winds. The Great American Dust Storm of 12 November 1933, which marked the beginning of the Dust Bowl, stretched from Canada to western Ohio and the Missouri Valley, an area larger than France, Italy and Hungary! The increased frequency of dust storms in the USA was due to severe drought and poor agricultural techniques. Although the land was not desert, it took on desert characteristics. In the 1970s, there was an increase in the number of dust storms in the Sahel region of Africa. Some of these storms travelled across the Atlantic to reach the Caribbean and were also associated with an increase in asthma there, partly as a result of increased dust, and partly as a result of the transfer of bacteria by winds across the Atlantic Ocean. Finally, as already noted, during the last glaciations some areas in the tropics were wetter and some were drier. It is estimated that the rate of dust removal and deposition was 100 times greater than it is at present.

Erosion

By itself, wind can only blow away loose, unconsolidated material so gradually lowering the surface by deflation. At wind speeds of 40 kilometres per hour, sand grains will move by surface creep and saltation. Much transport of sand will therefore be limited to a metre or so above the surface (Figure 10.6). Most abrasion (corrasion) occurs in this zone, by sand particles hitting against rocks. Higher wind speeds will cause dust storms. Extremely rare gusts of over 150 kilometres per hour are needed to roll pebbles along the ground. Fine dust is moved easily by light winds.

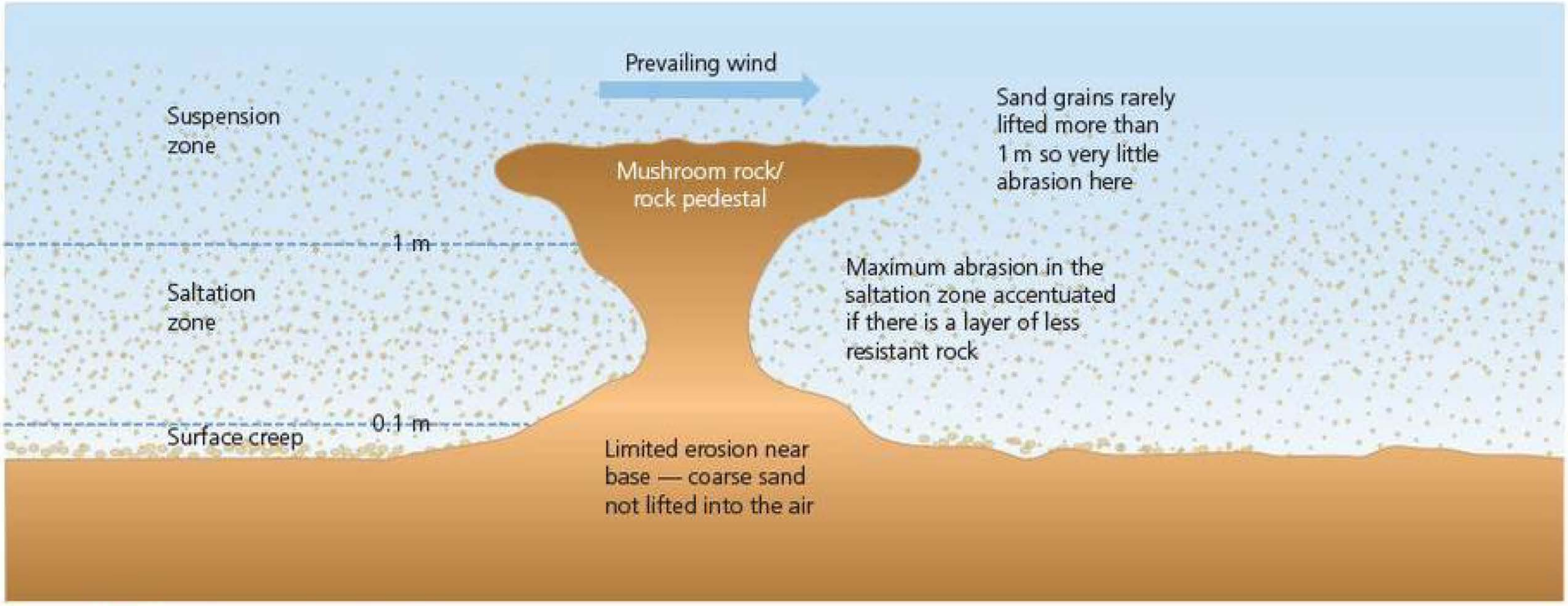


Figure 10.6 Wind transport and erosion

Transport

Sand-sized particles are well suited to transport by the wind. Sand movement occurs when wind speeds exceed 20 kilometres per hour. Grains initially begin to roll (traction), and then follow a bouncing action, known as saltation. The saltating grains are typically 0.15–0.25 millimetres in diameter. In contrast, larger grains (0.26–2 millimetres) move by surface creep and smaller grains (0.05–0.14 millimetres) move through **suspension**.

Deposition

Deposition occurs when the wind speed is reduced. The form taken by the deposited material is influenced by:

- the nature of any surface irregularity
- the amount and type of material carried by the wind, itself controlled by velocity
- the flow pattern of the dominant wind (shaping the material being deposited)
- the presence or absence of vegetation and groundwater.

Deserts occupy about 20 per cent of the world and their area is expanding. For example, the arid belt of the southern Sahara, known as the Sahel, has extended considerably into the savanna lands of Ethiopia, causing widespread famine there.

Sand drifts (temporary pockets of sand found in 'wind shadow' areas) and sand sheets (wide areas of flat or undulating sandscape) are common in desert areas. However, the formation of different types of sand dune seems to typify desert deposition.

Characteristic landforms of wind action

As well as blowing away layers of unconsolidated material over wide areas, deflation can be localised to produce deflation basins. It is not fully understood why localised deflation occurs – faulting may produce the initial depression that is enlarged by the eddying nature of the wind; differential erosion could also cause the initial trigger, as could solution weathering in a past **pluvial** period. Many such basins are found in the Sahara west of Cairo. Some basins have become so deflated that their bases reach the water table and so form an oasis, for example the Baharia and Farafra oases and the massive Qattara Depression, which lies 128 metres below sea level.

Selective deflation causes various different types of desert landscape:

- **hammada desert** – all loose material is blown away, leaving large areas of bare rock, often strewn with large, immovable weathered rocks
- **desert pavement** – pebbles are concentrated, for example by a flash flood, and packed together into a mosaic; the tops are then worn flat by wind erosion and perhaps become shiny as a coat of desert varnish develops
- **reg desert** – here, the finest material has been deflated, leaving a gravelly or stony desert
- **erg desert** – this is the classic sandy desert.

Wind erosion only takes place when the wind is loaded with loose materials, especially sand grains. Dust particles are ineffective. The wind throws the particles of sand against rock faces, creating abrasion or corrasion (a sand-blast effect). Large rock fragments, too heavy to be transported by the wind, are worn down on the windward side – these worn fragments are called ventifacts.

In areas of homogeneous rock, the wind will smooth and polish the surface. However, if the rocks are heterogeneous, for example weakened by joints or faults, some dramatic landforms will result from wind erosion, with rock faces etched, grooved, fluted and honeycombed, forming towers, pinnacles and natural arches. Undercutting (abrasion occurring at about 1 metre above the ground) is common, and produces distinctive landforms, including:

- gours – mushroom pinnacles where the base has been undercut, and bands of hard and soft rock have been differentially sand-blasted
- zeugens – develop where differing rock strata lie horizontally; after being eroded by the wind, the rocks form small plateau-like blocks that are isolated residuals of the original plateau, called 'mesas' (if quite large) and 'buttes' (if relatively small) in parts of Colorado, USA
- yardangs – occur where hard and soft rocks lie side by side; the softer rocks are worn down to form troughs, while the harder rocks stand up as wind-worn ridges or yardangs.

Wind-borne material is in constant motion and consequently attrition of this material occurs, the particles becoming rounder and smaller. Wind rounds material more effectively than running water because:

- wind speeds are greater
- distances over which the attrition takes place are often much greater
- the grains are not protected by a film of water.

Section 10.2 Activities

Outline the ways in which wind can erode desert surfaces.

Sand dunes

Only about 25–33 per cent of the world's deserts are covered by dunes, and in North America only 1–2 per cent of the deserts are ergs (sandy deserts) (Table 10.4). Large ergs are found in the Sahara and Arabia. The sand that forms the deserts comes from a variety of sources: alluvial plains, lake shores, sea shores and from weathered sandstone and granite.

The geometry of dunes is varied and depends on the supply of sand, the wind regime, vegetation cover and the shape of the ground surface.

Some dunes are formed in the lee of an obstacle. A nebkha is a small dune formed behind a tree or shrub, whereas a lunette dune is formed in the lee of a depression (Figure 10.7). Lunettes may reach a height of about 10 metres. They are asymmetric in cross-section, with the steeper side facing the wind. However, most dunes do not require an obstacle for their formation.

Barchan dunes are crescent-shaped and are found in areas where sand is limited but there is a constant wind supply. They have a gentle windward slope and a steep leeward slope up to 33°. Variations include barchan ridges and tranverse ridges, the latter forming where sand is abundant, and where the wind flow is checked by a topographic barrier, or increased vegetation cover. Barchans can be as wide as 30 metres.

Parabolic dunes have the opposite shape from barchans – they are also crescent-shaped but point downwind. They occur in areas of limited vegetation or soil moisture.

Linear dunes or seifs are commonly 5–30 metres high and occur as ridges 200–500 metres apart. They may extend for tens, if not hundreds, of kilometres. They are found in areas where there is a seasonal change in wind direction. It is believed that some regularity of turbulence is responsible for their formation (Figure 10.8).

Where the winds come from many directions, star dunes may be formed. Limbs may extend from a central peak. Star dunes can be up to 150 metres high and 2 kilometres wide.

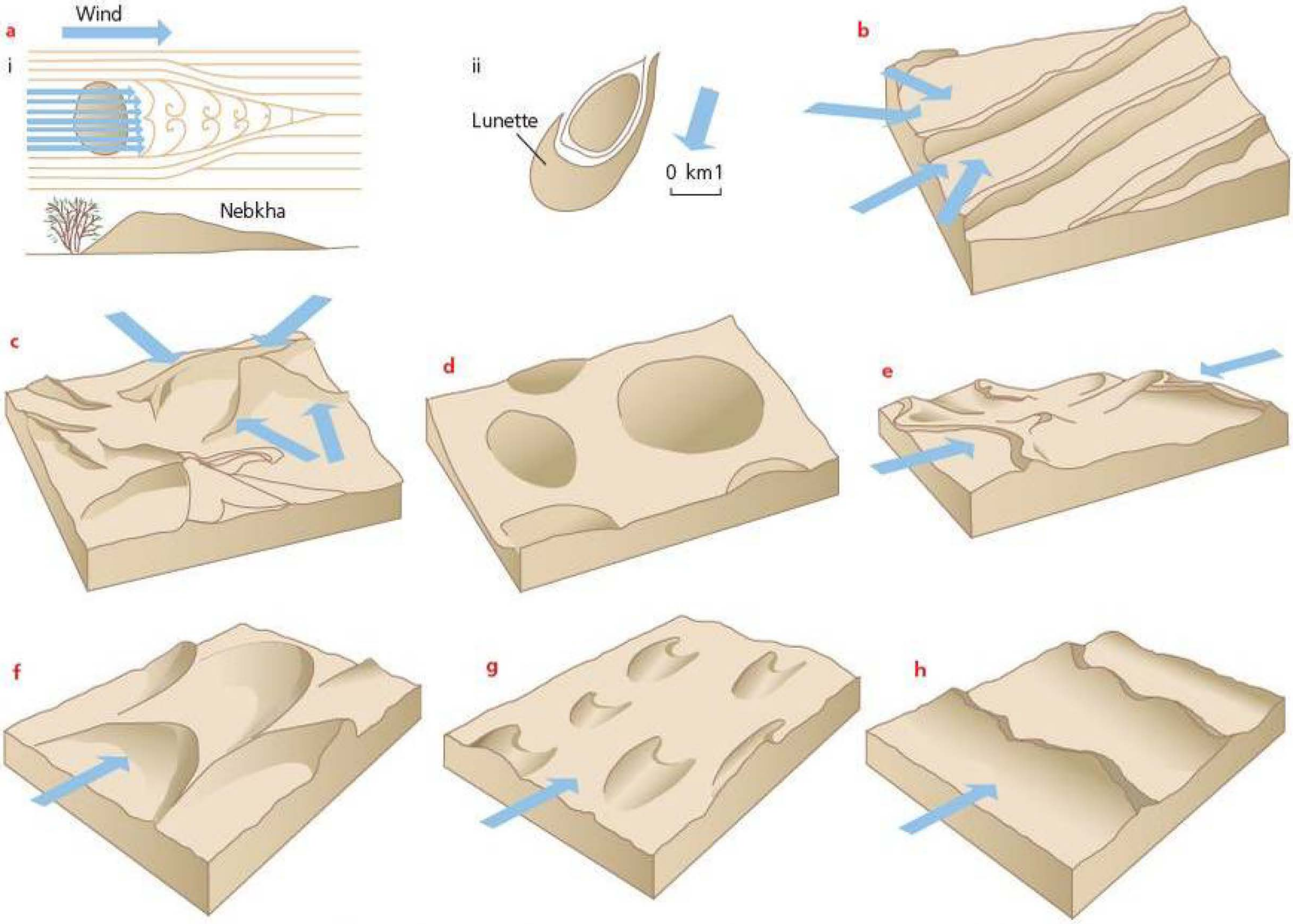
Dune types can merge. Crescent barchans can be transformed into longitudinal seif dunes, depending on the wind regime. The overemphasis on barchans and seif dunes is somewhat misleading. Less than 1 per cent of sand dunes are of these types. Dunes are not necessarily longitudinal or transverse – many are oblique. Grain size is also important – coarse sand is associated with rounded dunes, of subdued size and long wavelength. Fine sand produces stronger relief with smaller wavelengths.

Section 10.2 Activities

Comment on the regional distribution, and relative importance, of linear dunes, as shown in Table 10.4.

Table 10.4 The relative importance (percentage figures) of major dune types in the world's deserts

Desert	Thar	Takla Makan	Namib	Kalahari	Saudi Arabia	Ala Shan	South Sahara	North Sahara	North-east Sahara	West Sahara	Average
Linear dunes	13.96	22.12	32.84	85.85	49.81	1.44	24.08	22.84	17.01	35.49	**30.54**
Crescent dunes	54.29	36.91	11.80	0.59	14.91	27.01	28.37	33.34	14.53	19.17	**24.09**
Star dunes	–	–	9.92	–	5.34	2.87	–	7.92	23.92	–	**5.00**
Dome dunes	–	7.40	–	–	–	0.86	–	–	0.8	–	**0.90**
Sheets and streaks	31.75	33.56	45.44	13.56	23.24	67.82	47.54	35.92	39.25	45.34	**38.34**
Undifferentiated	–	–	–	–	6.71	–	–	–	4.50	–	**1.12**



a Dune formation
b Linear dunes or seifs
c Star dunes
d Dome dunes
e Reversing dunes
f Parabolic dunes
g Barchan dunes
h Barchanoid ridge

Figure 10.7 Some sand dune types

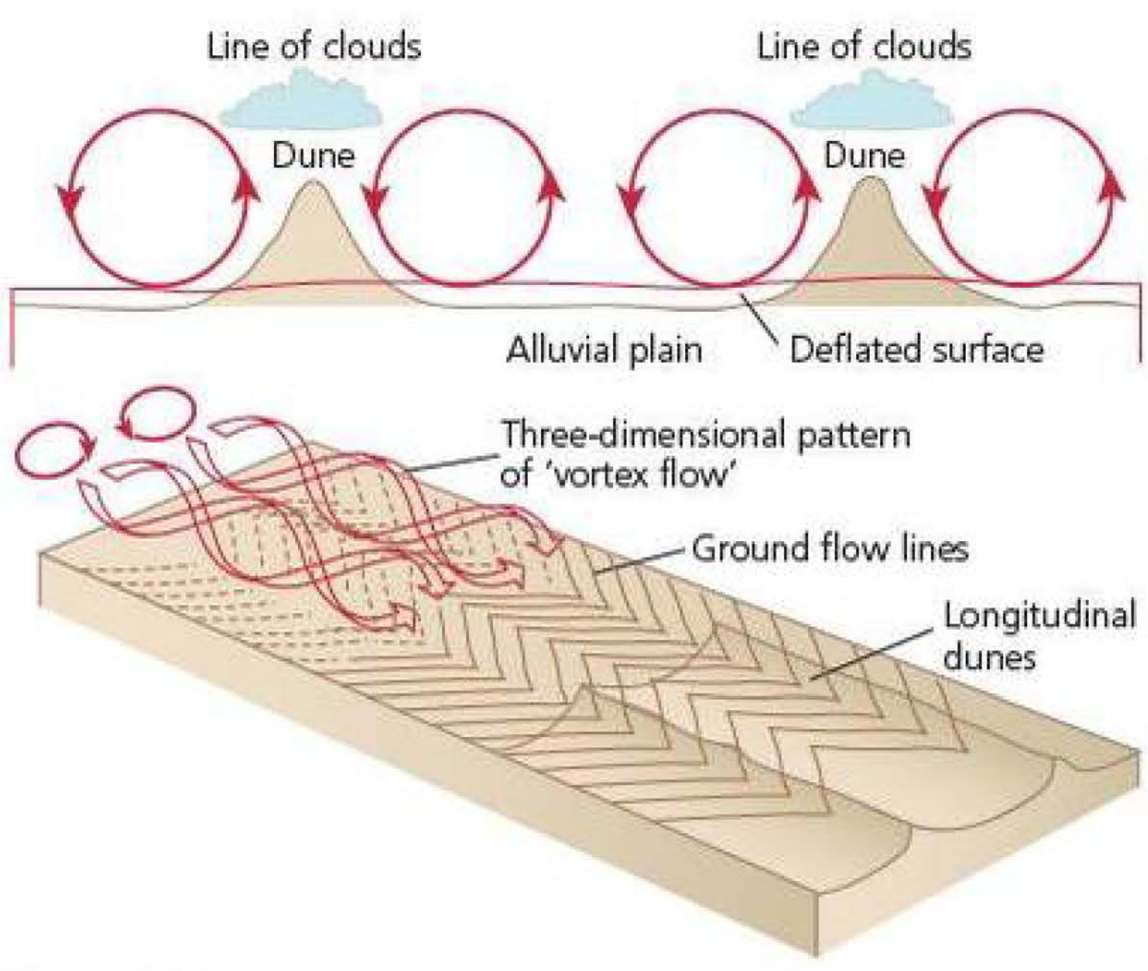


Figure 10.8 Turbulence and the formation of seif dunes

Water action and its characteristic landforms

Despite the low rainfall in arid regions, rivers play an important part in the development of many arid landforms. The **hydrological regime** (annual and seasonal pattern) is very irregular and can be unpredictable. Rainfall may be irregular and **episodic** (sporadic) but some desert areas experience occasional heavy downpours. These downpours may generate sudden **flash floods** and **sheet floods** (where the water is not confined in an identifiable channel).

Rivers in arid lands can be divided into three types:

- **Exogenous** rivers have their origin in humid areas – they are exotic rivers. The Nile flows through the Sahara but rises in the monsoonal Ethiopian Highlands and in equatorial Lake Victoria.
- **Endoreic** rivers flow into inland lakes. The Jordan River flows into the Dead Sea and the Bear River flows into the Great Salt Lake.

- Ephemeral rivers flow only after rainstorms. They can generate high amounts of discharge because torrential downpours exceed the infiltration capacity of the soils. Most ephemeral streams consist of many braided channels separated by islands of sediment.

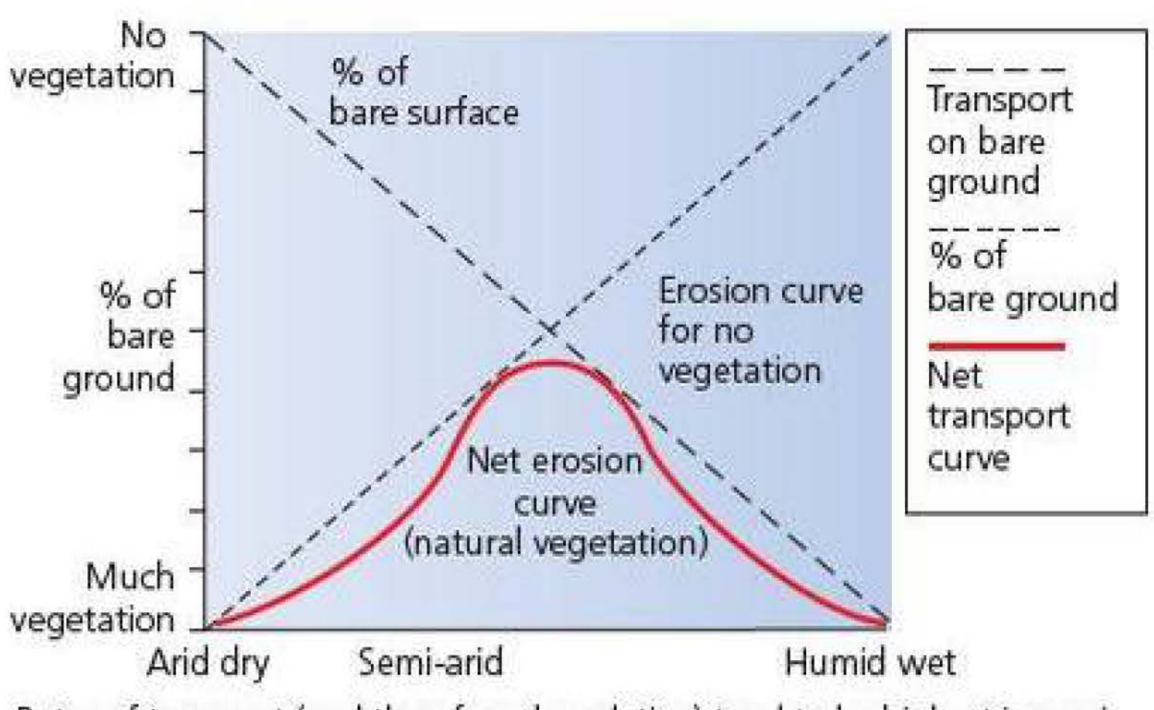
Even areas of low-intensity rain can generate much overland flow. This is because of the lack of vegetation and the limited soil development. The presence of duricrusts also reduces the ability of water to infiltrate the soil.

Surface runoff is typically in the form of sheet flow, where water flows evenly over the land. The runoff may become concentrated into deep, steep-sided valleys known as wadis or arroyos.

Stream flow in dry areas is seasonal, and in some cases erratic. This increases the potential for flooding due to a combination of:

- high velocities
- variable sediment concentrations
- rapid changes in the location of channels.

According to some geographers, erosion is most effective in dry areas. This is because of the relative lack of vegetation. When it rains, a large proportion of rain will hit bare ground, compact it and lead to high rates of overland runoff. By contrast, in much wetter areas such as rainforests, the vegetation intercepts much of the rainfall and reduces the impact of rainsplash. At the other extreme, areas that are completely dry do not receive enough rain to produce much runoff. Hence it is the areas that have variable rainfall (and a variable vegetation cover) that experience the highest rates of erosion and runoff (Figure 10.9). Moreover, as the type of agriculture changes, the rate of erosion and overland runoff change (Figure 10.10). Under intense conditions this creates gullies.



Rates of transport (and therefore denudation) tend to be highest in semi-arid areas and especially in more humid areas where vegetation is removed

Figure 10.9 Rainfall, vegetation cover and soil erosion

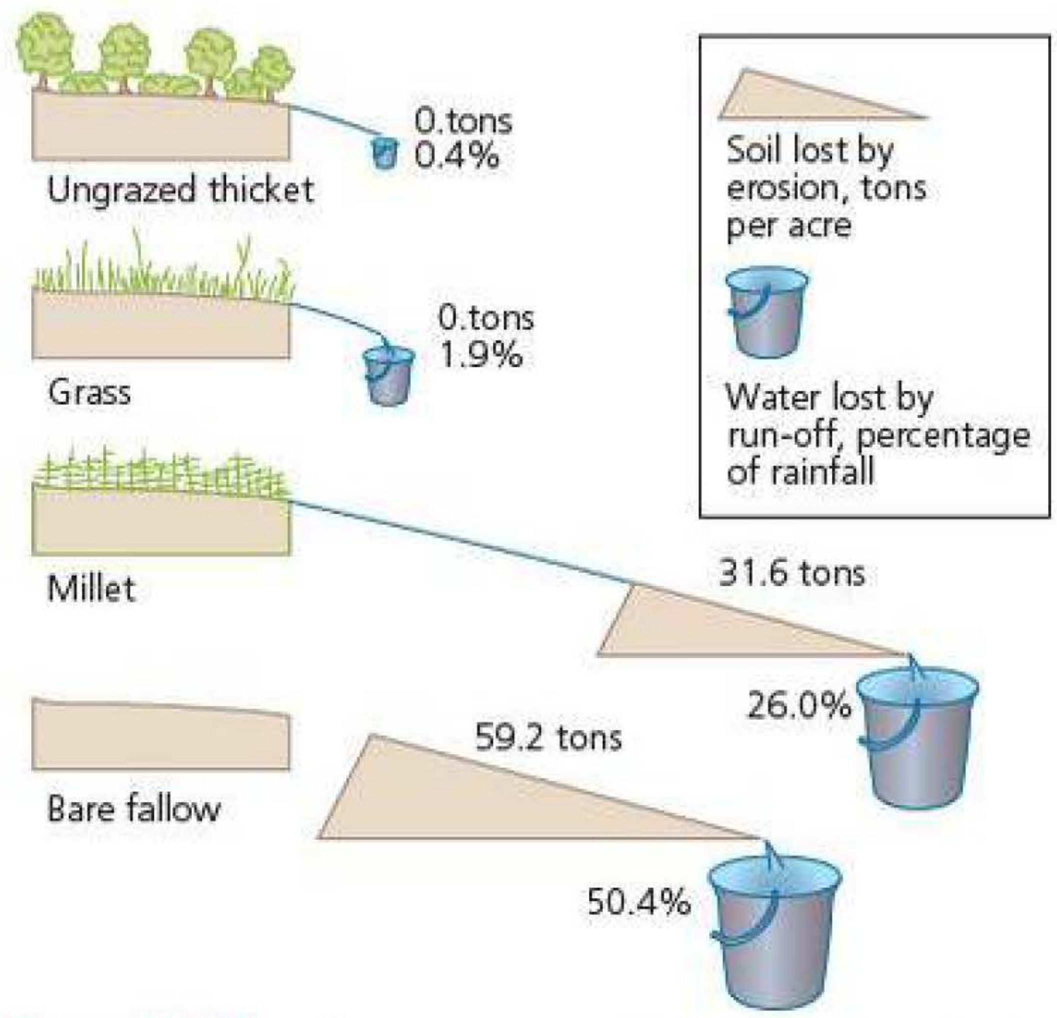


Figure 10.10 The impact of vegetation type on runoff and soil erosion

There is a paradox that in deserts most runoff occurs on low-angle slopes. This is due to particle size. Coarse debris makes up the steeper slopes, while fine material makes up the low-angle slopes. Coarse debris allows more infiltration, so there is less overland flow on steeper slopes.

High concentrations of sediment in runoff from desert uplands illustrate (a) the erodibility of unvegetated areas and (b) the contemporary nature of the work of water in deserts. Desert streams are cloudy and muddy – up to 75 per cent of the flow may be solid matter. This solid matter is important for the formation of alluvial fans (and for silt building up behind dams). An alluvial fan is a cone of sediment occurring between a mountain and a lowland plain; that is, the piedmont zone (literally the foot of the mountain) (Figure 10.11). They can be up to 20 kilometres wide and up to 300 metres at the apex. They generally form when a heavily sediment-laden river emerges from a canyon. The river, no longer confined to the narrow canyon, spreads out laterally, losing height, energy and velocity, so that deposition occurs; larger particles are deposited first and finer materials are carried further away from the mountain. If a number of alluvial fans merge, the feature is known as a bajada (bahada).

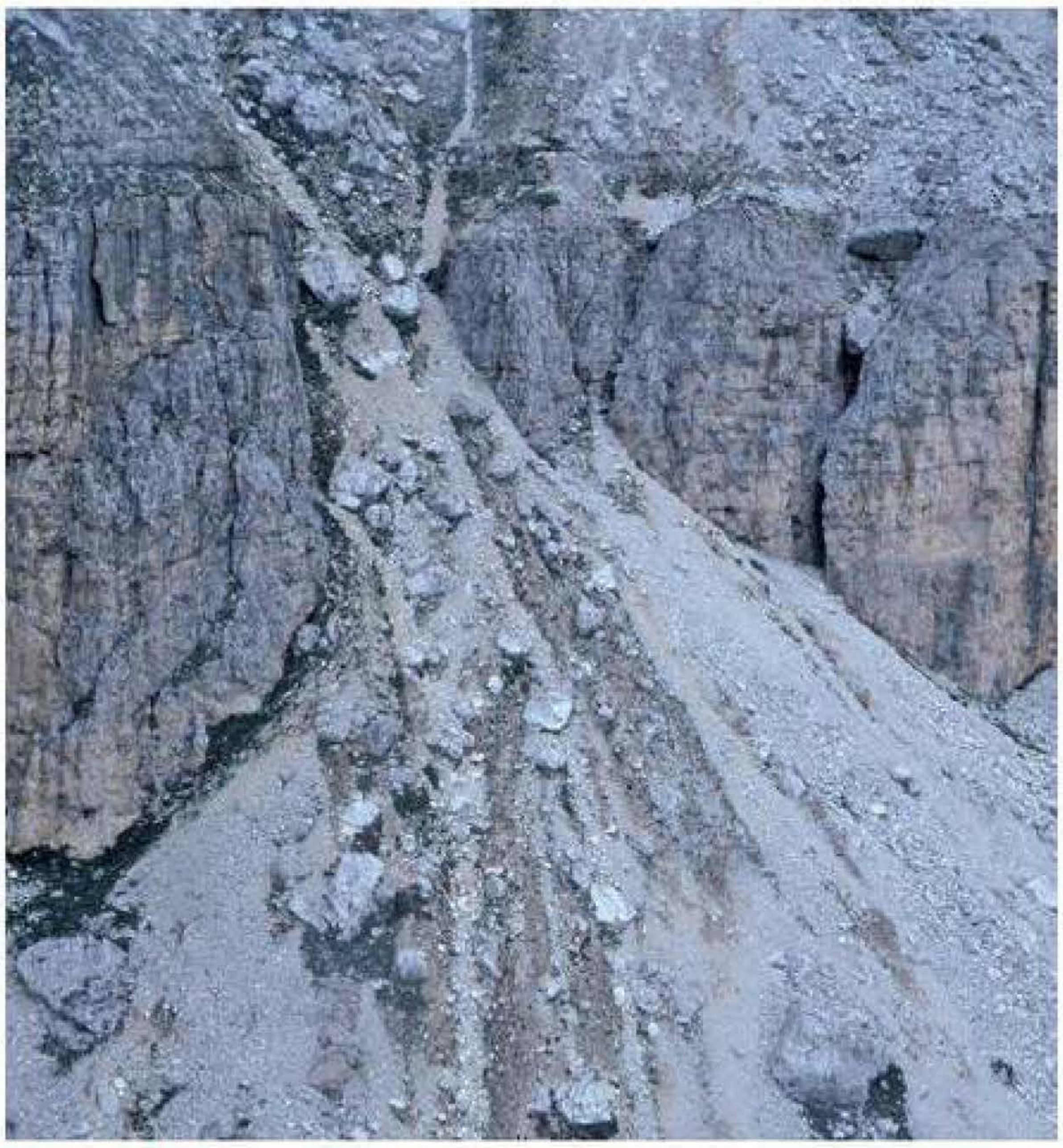


Figure 10.11 An alluvial fan

On a larger scale, pediments are gently sloping areas ($< 7°$) of bare rock where there is a distinct break with the mountain region (Figure 10.12). One idea is that they are the result of lateral planation. Another hypothesis involves sub-surface weathering. This is likely to be accentuated at the junction of the mountain and the plain because of the concentration of water there through percolation. The weathering will produce fine-grained material that can be removed, in the absence of vegetation cover, by sheetfloods, wind and other processes.

Salt lakes (chottes/playas) are found in the lowest part of the desert surface, where ephemeral streams flow into inland depressions, for example the Chott el Djerid of Tunisia. After flowing into the depression, water evaporates, leaving behind a thick crust. Sodium chloride is the most common salt found in such locations, but there could also be gypsum (calcium sulphate), sodium sulphate, magnesium sulphate and potassium and magnesium chlorides.

In some semi-arid areas, water action creates a landscape known as badlands. These are areas where soft and relatively impermeable rocks are moulded by rapid runoff that results from heavy but irregular rainfall. There is insufficient vegetation to hold the regolith and bedrock together, and rainfall and runoff are powerful enough to create dramatic landforms. Badlands generally have the following features:

- wadis of various sizes with debris-covered bottoms
- gullies that erode headwards, leading to their collapse
- slope failure and slumping
- alluvial fans at the base of slopes
- natural arches formed by the erosion of a cave over time.

An excellent example of badland topography is in southern Tunisia around Matmata.

Wadis are river channels that vary in size from a few metres in length to over 100 kilometres. They are generally steep-sided and flat-bottomed. They may be formed by intermittent flash floods or they may have been formed during wetter pluvial periods in the Pleistocene. The relative infrequency of flash floods in some areas where wadis are found could suggest that they were formed at a time when storms were more frequent and more intense. In contrast, **arroyos** are channels that have enlarged by repeated flooding. They are common in semi-arid areas on alluvium and solid rock.

Mesas are plateau-like features with steep sides at their edges. Buttes are similar but much smaller. Water has eroded most of the rock, leaving a thin pillar. Inselbergs (see Topic 7, Section 7.2) may be the result of deep chemical weathering during wetter pluvial periods. Overlying sediments were subsequently removed by river activity. They are isolated steep-sided hills. A good example is Uluru (Ayers Rock) in Australia.

High runoff and sediment yields cause much dissection and high drainage densities (total length of water channel per km^2). In the Badlands of the USA, drainage densities can be as high as 350 km/km^2, whereas in a typical temperate region it is 2–8 km/km^2. In contrast, in sandy deserts (high infiltration), drainage densities can be as low as 0–1 km/km^2.

Section 10.2 Activities

1 Study Figure 10.9, which shows the relationship between rainfall, vegetation cover and erosion.
   a Why is there limited erosion in areas where rainfall is very low?
   b Why is there limited erosion in areas where rainfall is very high?
   c Why are there high rates of erosion in areas with about 600 millimetres of rain?

2 Figure 10.10 shows the effects of crop type on runoff and erosion. Describe what happens when scrubland (ungrazed thicket) is used for either pastoral agriculture (grass) or arable agriculture (millet). Describe and explain the effects of the removal of vegetation on runoff rates and erosion rates.

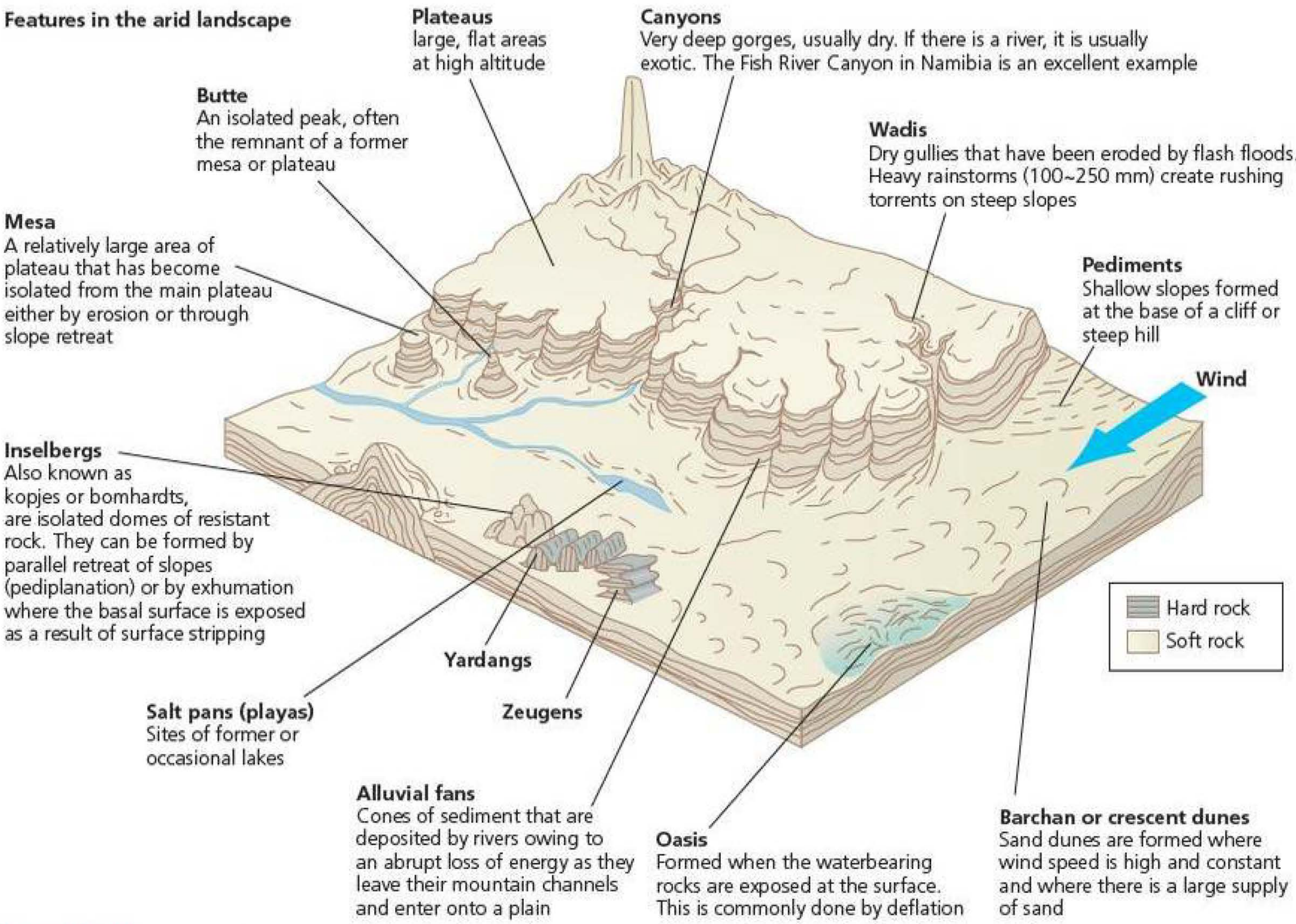


Figure 10.12 Desert landforms

□ Relative roles of aeolian and river processes

Evidence of past climate change in deserts

During the Pleistocene Ice Age, high latitudes contained more ice (30 per cent of the world surface) than today (10 per cent of the world surface), while low-latitude areas experienced increased rainfall – episodes known as 'pluvials'. Some deserts, however, received less rainfall – these dry phases are known as 'interpluvials'.

There is widespread evidence for pluvial periods in deserts (Figure 10.13):

- shorelines marking higher lake levels around dry, salty basins
- fossil soils of more humid types, including horizons containing laterite
- spring deposits of lime, called 'tufa', indicating higher groundwater levels
- river systems now blocked by sand dunes
- animal and plant remains in areas that are now too arid to support such species
- evidence of human habitation, including cave paintings.

Wetter conditions existed in the tropics, causing lakes to reach much higher levels and rivers to flow into areas that are now dry. On the margins of the Sahara, Lake Chad may have been 120 metres deeper than it currently is, and may have extended hundreds of kilometres north of its present position.

The evidence for drier conditions includes sand dune systems in areas that are now too wet for sand movement to occur. Dunes cannot develop to any great degree in continental interiors unless the vegetation cover is sparse enough to allow sand movement. If the rainfall is much over 150 millimetres, this is generally not possible. Satellite imagery and aerial photographs have shown that some areas of forest and savanna, with 750–1500 millimetres of rain, contain areas of ancient degraded dunes. Today, about 10 per cent of the land area between 30°N and 30°S is covered by active sand deserts, but about 18000 years ago this area was about 30 per cent sand desert.

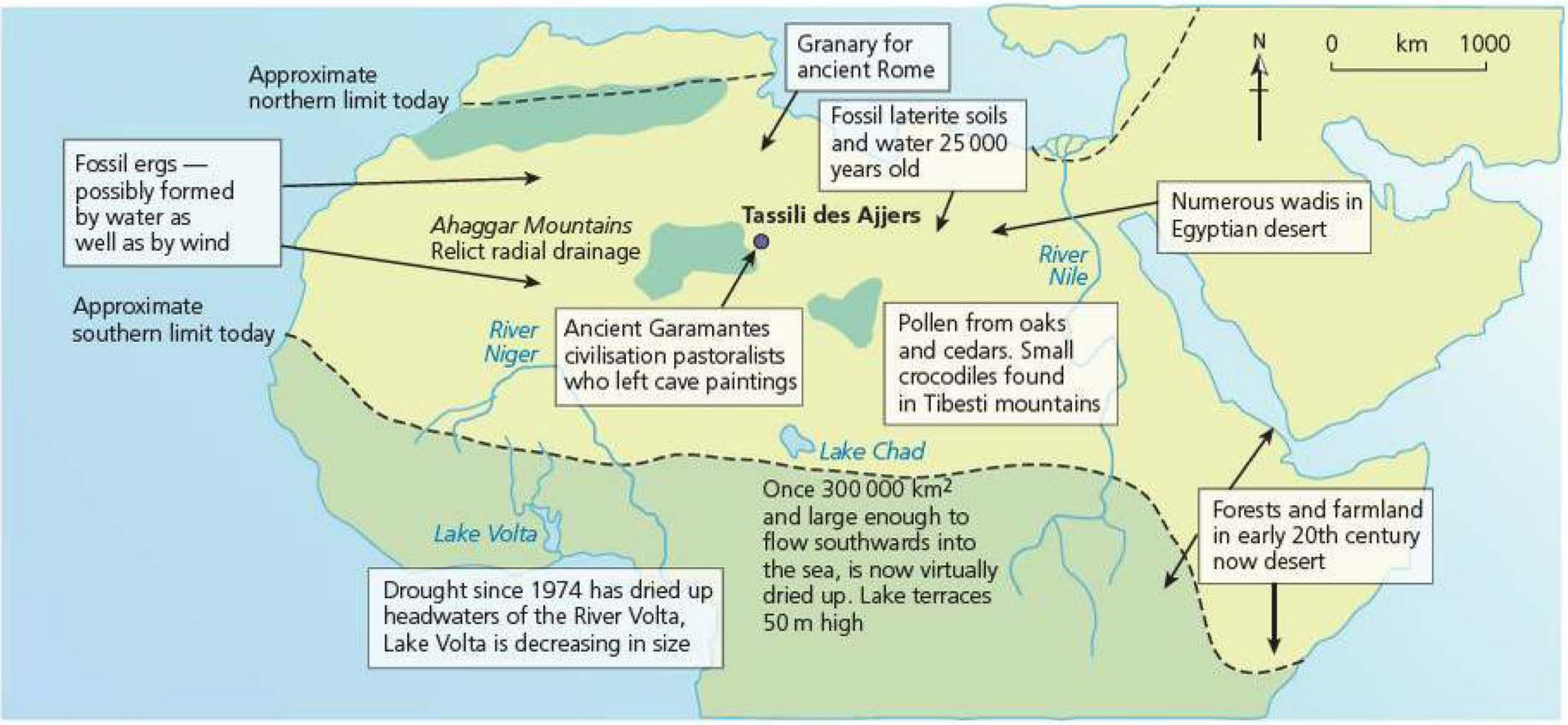


Figure 10.13 The evidence for climate change in the Sahara

Case Study: Climate change in Australia

Glacial periods triggered decreased rainfall and increased windiness. At least eight episodes of dune building have occurred over the last 370 000 years. The largest sand dune system in the world is the Simpson desert, which was formed only 18 000 years ago. The Simpson desert covers 159 000 km^2 and consists of linear dunes 10–35 metres high and up to 200 kilometres long (Figure 10.14). They run parallel to each other, with an average spacing over 510 metres. The dunes are fixed (vegetated) except for their crests, which are mobile. The Simpson desert dunes form part of a continental anticlockwise swirl that relates to the dominant winds of the subtropical anticyclone system.

Figure 10.14 Dunes in Australia

Section 10.2 Activities

Examine the evidence to suggest that some deserts in the past were **a** wetter and **b** drier.

Equifinality: different processes, same end product

A question frequently asked is whether desert landforms are the result of wind action or water action. This is a simplification because there are other processes than wind and water acting in desert regions. For example, stone pavements are surfaces of coarse debris lying above finer material. They could be caused by:

- deflation of fine material, leaving coarse material behind
- removal of fine material by rainsplash or sheetwash
- vertical sorting by frost action or hydration.

It may even be a combination of processes.

Similarly, depressions can be caused by a variety of processes:

- deflation removing finer material, as in the Qattara Depression, Sahara
- tectonic, for example block faulting in the basin and range region of the USA
- solution of limestone during a pluvial period as, for example, in Morocco
- animal activity as, for example, in Zimbabwe where herds are concentrated near water holes and accentuate the initial depression.