10 Hot arid and semi-arid environments

In this chapter you will learn about:

→ The climate of the hot arid and semi-arid areas and why they are so dry.

→ How the wind has led to the formation of relief features in the hot arid and semi-arid areas and how violent rainstorms, past and present, have also had an effect.

→ The special soils and vegetation of hot arid and semi-arid areas and how deserts may be spreading as a result of human activity.

→ The environmental problems of the Sahel region of Africa and how they might be managed.

Hot and semi-arid climates

Definitions of aridity (dryness)

Effective precipitation

The simplest way to define what is a desert is to look at the mean annual precipitation. The 250 millimetre **isohyet** will correspond approximately to the boundaries of the deserts (an isohyet is a line of equal precipitation on a map). However, the aridity of a region depends not just on the amount of precipitation the area receives, but also on the effectiveness of the precipitation - in other words the moisture available for plant growth. Various empirical formulae have been used to attempt to obtain values of effective precipitation. These formulae usually include measures of precipitation and **potential evaporation** or **evapotranspiration**. This is the amount of evaporation (water vapour loss from water surfaces) and transpiration (water vapour loss from plants) that would occur if sufficient water supplies were available. It is affected by surface and air temperatures, insolation (the energy emitted by the sun) and wind. High temperatures, direct sun and strong desiccating winds all increase evaporation losses. The actual evapotranspiration will often be less than the potential evapotranspiration. In arid areas, annual potential evaporation exceeds annual precipitation. Potential evapotranspiration can be measured using an open pan of water left in direct sunlight. Actual evapotranspiration is measured using a **lysimeter**, a pan of soil and vegetation. The pan is topped up with water and changes in weight indicate the amount of evapotranspiration occurring.

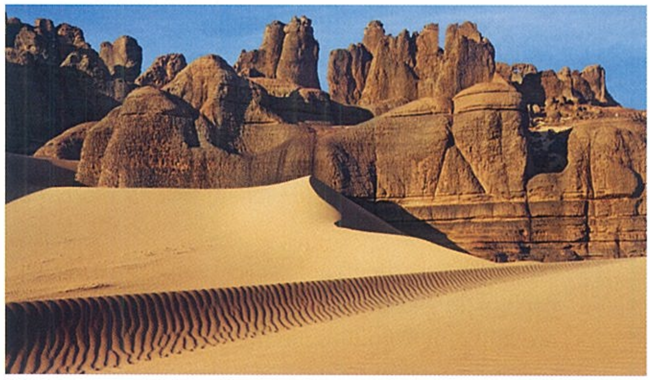

Fig. 10.1 A sand and rock desert in the Sahara, Algeria

Degrees of aridity

Different textbooks show maps of the world's deserts which have slight differences depending on how aridity is defined. One system of classification uses the amount by which mean annual potential evapotranspiration (Etp) exceeds mean annual precipitation (P).

Region	P compared to Etp
Hyper-arid	P less than 0.03 × Etp
Arid	P between 0.03 and 0.20 × Etp
Semi-arid	P between 0.20 and 0.50 Etp

Table 10.1 Definitions of aridity

In these regions Etp exceeds P by a factor of two or more. The regions cover about one-third of the world's land surface.

A. A. Miller

The climatologist A. A. Miller simply defined deserts as areas with a mean annual precipitation less then 250 millimetres. Miller then made a distinction between the hot (tropical) deserts and the mid-latitude (temperate) deserts.

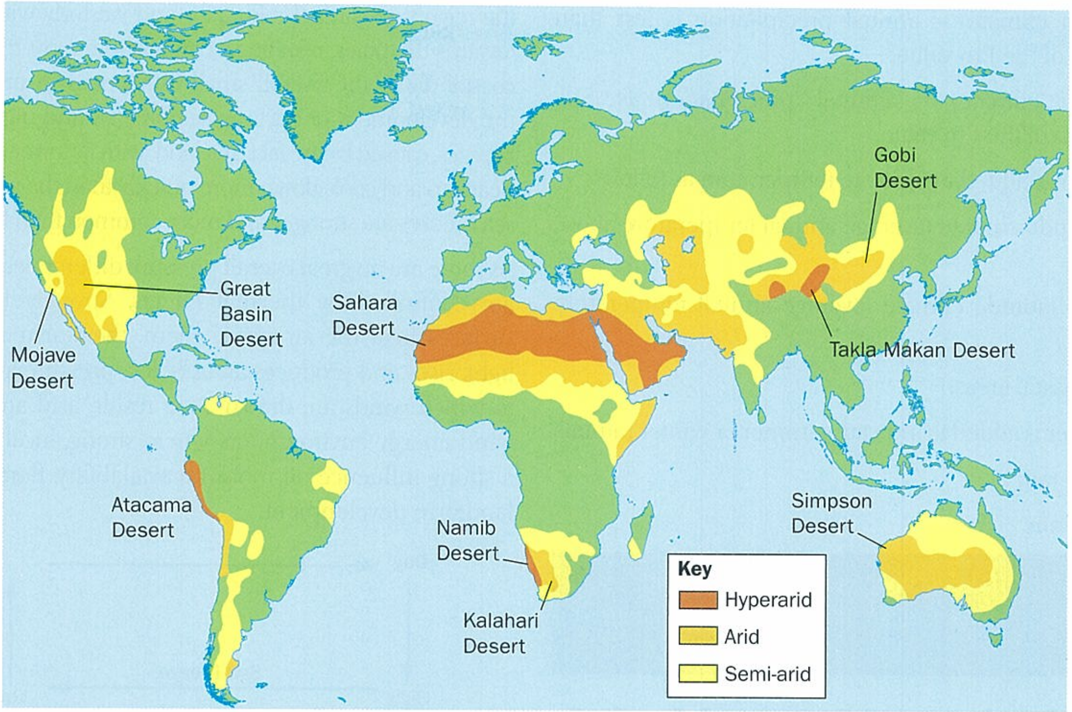

Fig. 10.2 The world distribution of hyperarid, arid and semi-arid areas

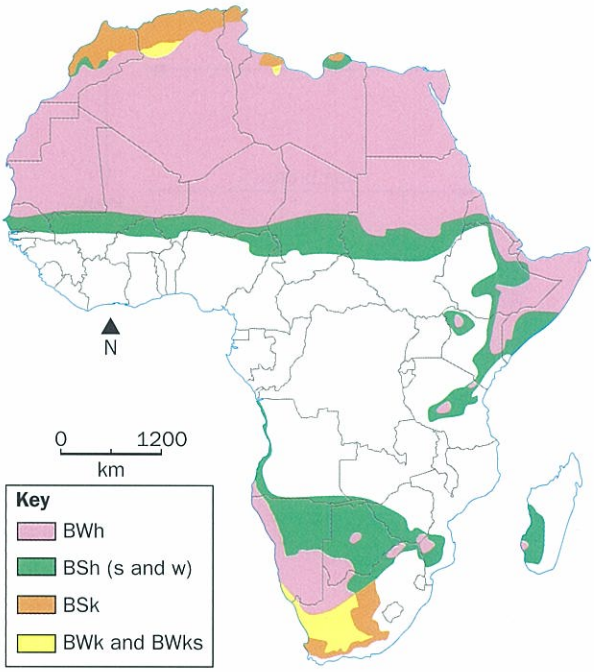

Fig. 10.3 A simplified map of arid climates in Africa using the Köppen classification

Miller defined hot climates as having no month with a mean temperature of less than 6 °C. Miller's hot deserts are not totally confined within the tropics and include the Mojave/North Mexico, Atacama, Sahara, Kalahari/Namib, Arabian, Iranian, Thar and Great Australian deserts. Most of the Miller's hot deserts are located in latitudes from 15 ° to 30 ° astride the Tropics on the western sides of continents. However, the Mojave desert in south-west USA and the Mexican desert, as well as the Iranian and Thar deserts, have this type of climate, but lie in the sub-tropics north of the Tropic of Cancer and extend to 40 °N.

Miller's mid-latitude deserts, with a cold season with at least one month with a mean temperature of less than 6 °C, include the Great Basin of North America, southern Patagonia and the Gobi and Takla deserts.

W. Köppen

The Russian-German climatologist W. Köppen produced a classification based on the P:Etp balance. Arid climates are shown by the letter B. P is less than the Etp, calculated using the average annual temperature as shown below.

A second letter shows the degree of aridity based on Etp values in millimetres, calculated as follows:

1. Multiply the average annual temperature in °C by 20.
2. Add:
   (a) 280 if 70 per cent or more of the total precipitation is in the high sun half of the year (April through September in the northern hemisphere, or October through March in the southern hemisphere), or
   (b) 140 if 30–70 per cent of the total precipitation is received during the applicable period, or
   (c) 0 if less than 30 per cent of the total precipitation is received during the applicable period.

BW (desert climate) = annual precipitation is less than 50 per cent of the Etp value.

BS (steppe climate) = annual precipitation is 50–100 per cent of the Etp value.

A third letter is added to indicate temperature as follows:

h = low latitude climate (average annual temperature above 18 °C)

k = middle latitude climate (average annual temperature below 18 °C)

n = foggy coastal areas.

A fourth letter is added to indicate summer or winter rainfall:

s = summer rain

w = winter rain.

1. Using Fig. 10.3 describe the distribution of arid climates in Africa. Explain the meaning of each letter used.

Description of hot arid and semi-arid climates

Hot arid areas do not have a cold season, with no mean monthly temperatures falling below 6 °C. Rainfall totals are very low and generally below 250 millimetres. Cairo, Egypt has a mean annual rainfall of 33 millimetres and there are areas of the Atacama desert where rain has never been recorded. Generally, in arid areas rainfall is sporadic, unpredictable and torrential. It may only rain once every few years. Areas on the margins with the savannas, such as the Sahel on the southern margins of the Sahara, have rainfall in summer whereas areas on the margins with the areas of Mediterranean climate on the poleward margins have rainfall in winter.

In continental areas, such as the central Sahara, there are very high diurnal temperature ranges, frequently exceeding 30 °C. Daytime temperatures are the highest in the world. Shade temperatures of above 50 °C have been recorded, including 58 °C in 1922 at Aziza in Libya. There are night frosts in winter. In Salah in Algeria has a July mean of 37 °C. Annual ranges are not very high and are often around 15 °C.

Coastal areas such as the Namib and Atacama coastal margins have climates influenced by the sea and the cold, upwelling ocean currents. Summers are cooler; for example, at Walvis Bay, Namibia, the mean temperature of the hottest month is only 19 °C, resulting in an annual range of only 5 °C. Humidity levels are much higher than in the continental interiors. Fog forms over the cold ocean currents and is blown inland; this is a significant factor for flora and fauna.

The hot arid areas lie in the **'horse latitudes'**, the areas of the sub-tropical high pressure systems roughly 30 to 35° north and south of the equator. These are areas of descending air, gentle pressure gradients and calms. Easterly trade winds blow out of the regions towards the Equator and westerly winds blow out towards the poles, resulting in an offshore movement of air. In coastal areas, the overall small differences in pressure allow the development of daytime sea breezes and night-time land breezes, caused by the fact that land, with its lower specific heat, heats up and cools down more quickly than the sea. Generally, sea breezes are stronger and more common than land breezes.

As there are no great overall pressure differences, local winds are controlled by thermal effects. Strongly heated land surfaces heat the air above them, the warm air becomes light, rises and produces areas of low pressure at the surface to which winds are drawn. As a result, arid areas are high wind energy environments where strong, local winds have a strong influence on moisture availability, flora, fauna and landform development.

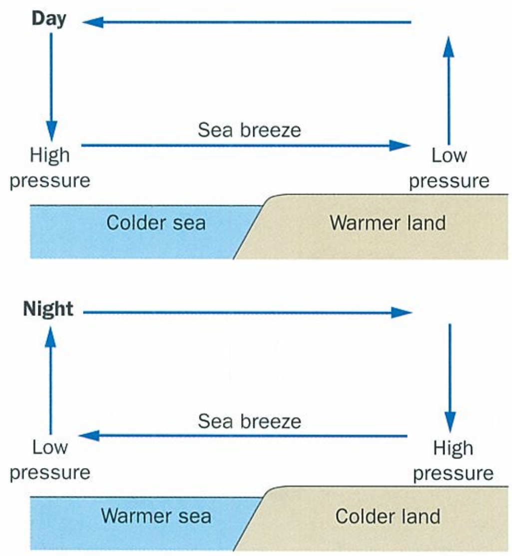

Fig. 10.4 The formation of land and sea breezes

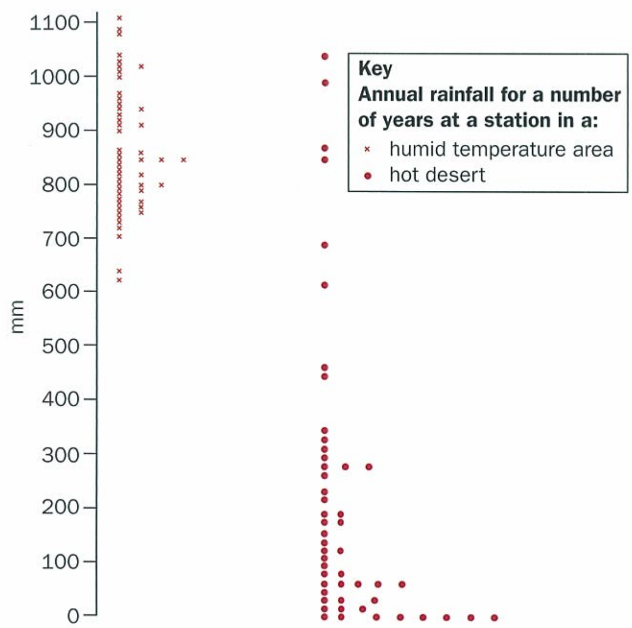

Fig. 10.5 Dispersion graphs showing the annual rainfall for a number of years at a station in a humid temperate area (crosses) and a station in a hot desert (circles)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean temp. (˚C)	19	18.5	18	17	16	15.5	14.5	14	15	16	17	18
Mean max. temp. (˚C)	22	22	22	21	20	20	19	18	19	20	21	22
Mean min. temp. (˚C)	16	15	14	13	12	11	10	10	11	12	13	14
Mean relative humidity (%)	75	78	75	74	74	66	67	70	74	75	73	72
Mean rainfall (mm)	0.4	1.4	3.6	10.5	4.1	5	2	1.5	1.3	0.7	0.7	2
Mean sunshine hours	10	9	9	9	9.5	9	9	9.5	19.5	10	10.5	11

Table 10.2 The climate of Luderitz, Nambia

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean temp. (˚C)	27	26.5	25	22.5	18	14	13	15.5	18.5	21	23.5	26
Mean max. temp. (˚C)	35	34	32	30	26	22	20	24	26.5	30	32	35
Mean min. temp. (˚C)	19	19	16	15	10	6	6	7	10.5	12	15	17
Mean relative humidity (%)	32	33	35	36	33	34	33	29	24	24	25	26
Mean rainfall (mm)	29	31.5	30	20.5	9	2	2	8	4	4.5	14.5	11.5

Table 10.3 The climate of Keetmanshoop, Nambia

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean max. temp. (˚C)	30.8	33.0	36.8	40.1	41.9	41.3	38.4	37.3	39.1	39.3	35.2	31.8	37.1
Mean temp. (˚C)	23.2	25.0	28.7	31.9	34.5	34.3	32.1	31.5	32.5	32.4	28.1	24.5	29.9
Mean min. temp. (˚C)	15.6	17.0	20.5	23.6	27.1	27.3	25.9	25.3	26.0	25.5	21.0	17.1	22.9
Rainfall (mm)	0	0	0	0.5	4	5	46	75	25	5	1	0	161.5

Table 10.4 The climate of Khartoum, Sudan

2. Explain how the climates shown in Tables 10.2, 10.3 and 10.4 show the typical features of coastal and continental arid areas.

The sporadic nature of desert rainfall can be shown by a dispersion graph. These graphs take various forms but they show how much a series of values vary from the mean.

3. Describe the differences in rainfall for the humid temperate area and the arid areas as shown by the two dispersion graphs.

The recurrence interval of an event is based on historical statistics and is an estimate of the probability of a particular event occurring. It is sometimes called the return period. The recurrence interval of rainfall events in a hot desert is shown by Fig. 10.6 and shows a lognormal distribution. Notice that the scale on the y axis is arithmetic but the scale on the x axis is logarithmic.

4. Describe the pattern of annual rainfall totals shown by Fig. 10.6. Why are the two scales different?

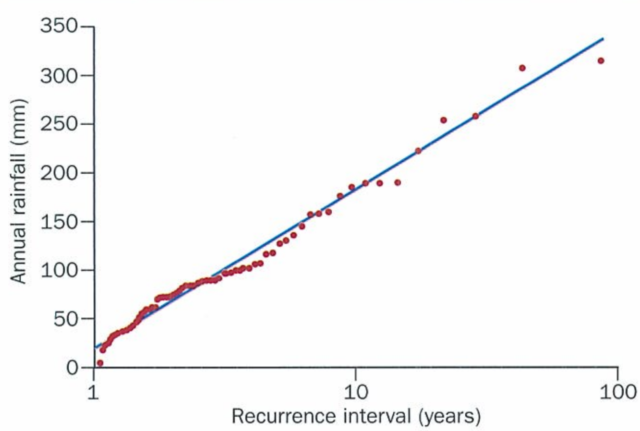

Fig. 10.6 The recurrence intervals of annual rainfall totals in a hot arid areas showing a lognormal distribution

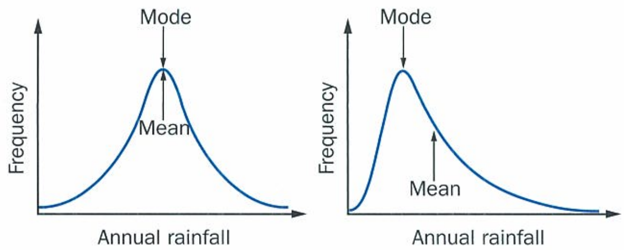

Fig. 10.7 Distribution curves for annual rainfall at two places, one showing a normal distribution and one showing a lognormal distribution

5. Describe the differences between the two distribution curves shown on Fig. 10.7. Which shows the rainfall in a hot arid area? Explain your answer.

The differences between the climates of hot arid and semi-arid areas

The hot arid and semi-arid areas are transitional with each other and share common features. Table 10.5 summarises some of the differences. The semi-arid climates are transitional with those of the savannas on the Equator side and the Mediterranean on the poleward side.

Reasons for the hot arid and semi-arid climates

Causes of aridity in deserts

Pressure and winds

The air that rises around the equator eventually descends in the horse latitudes of the hot deserts and this descending air is a major cause of their aridity. Having risen to the tropopause, the air moves towards the poles and cools, becoming denser as a result. It then sinks at about 30° N and 30° S, creating high pressure at the surface. Sinking air becomes compressed and compression causes warming which results in a decrease in its relative humidity. After reaching the surface, this dry air moves from the high pressure area back to the low pressure in equatorial latitudes as the trade winds. Some also moves towards the poles to the mid-latitude low pressure belts. The circulations of air between the equator and 30° N and 30° S are known as the Hadley cells.

The trade winds are strong and constant and, because they derive from sinking air and blow over land to the deserts, they do not contain much moisture. The combination of sinking air and dry, offshore trade winds is the main cause of the very low precipitation in the hot, arid areas. This explains why these areas occur on the west coasts of the continents rather than the east coasts. North-east trade winds blow in the northern hemisphere and south-east trade winds in the southern hemisphere. Their direction results from two controlling factors: winds blow out of high pressure systems into low pressure systems and they are deflected as they do so by the Earth's rotation.

Summer convectional rainfall occurs in areas on the margins with the savannas, such as the Sahel, on the southern margins of the Sahara. Winter rainfall due to depressions occurs on the margins of the areas of Mediterranean climate on the poleward margins of the deserts such as in the Maghreb in North Africa or southern Namibia.

Hot arid climates	Semi-arid climates
These areas occur in the centre of the desert areas including the arid and hyper arid areas shown on Fig. 10.2.	These areas occur on the margins of the arid areas including the semi-arid areas shown on Fig. 10.2.
This is Köppen's BW (desert) climate.	This is Köppen's BS (steppe) climate.
Annual average precipitation is less than 0.20 times the potential evapotranspiration – precipitation is very low and there is little moisture available for plant growth. Rainfall totals are generally below 250 mm and, in some regions, rainfall has not been experienced in living memory.	Annual average precipitation is between 0.20 and 0.50 times the potential evapotranspiration – precipitation is low but there is some moisture available for plant growth. For example, N'Djamena in Chad (part of the case study later in this chapter) has an annual average rainfall of 580 mm.
There is little seasonality to the rainfall. Rare, extreme rainfall events can occur in any season.	Rainfall is markedly seasonal. Those areas nearest to the Equator have a climate which is transitional with the savannas. Here summer rainfall occurs due to low pressure and monsoon influences. Those areas on the mid-latitude sides of the deserts have a climate which is transitional with Mediterranean climates and experience winter rainfall.
There is little difference in temperatures between the two climates. Latitude and distance from the sea are the most important factors which influence how extreme or moderate the temperatures are.	

Table 10.5 The differences between the climates of hot arid and semi-arid areas

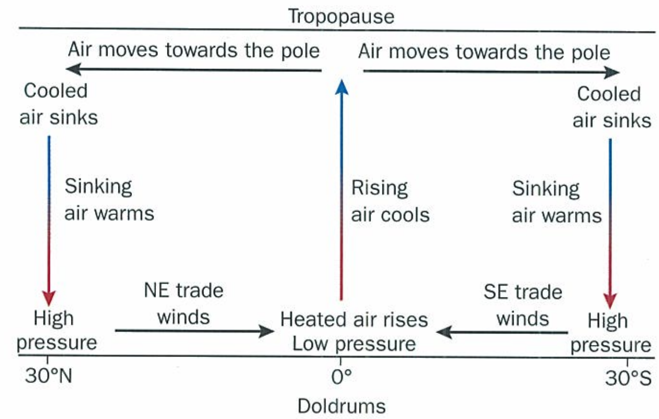

Fig. 10.8 The Hadley cells

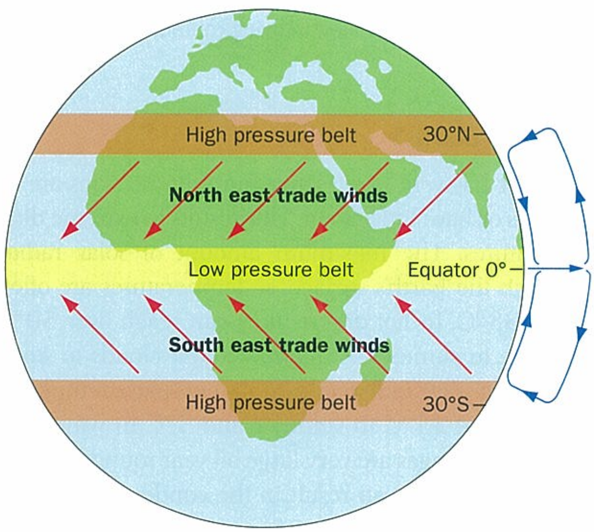

Fig. 10.9 The winds and pressure belts influencing the tropical desert climates

Cold ocean currents

As Fig. 10.10 shows, most hot arid and semi-arid areas occur on the west coasts of continents with a cold ocean current offshore. At times, when onshore winds blow on to the west coasts of deserts, they can be cooled sufficiently for condensation to occur over the current and coast, resulting in fog (tiny water droplets) hanging in the air near the surface, reducing visibility. Coastal places can have many foggy days and a relatively high humidity when the winds are onshore. This condensation removes moisture from the air. As the foggy air moves inland the water droplets quickly evaporate. Daytime warming as the air passes over the land further reduces its relative humidity and the chance of precipitation.

Relief and rainshadow

Areas of **relief (orographic) rainfall** and **rainshadow** (see Chapter 2) are found in deserts, although the amounts are small. Low areas in the lee of mountains, such as Death Valley in the USA or the Turfan Basin in China, can be extremely dry. Table 10.2 shows the climate of Luderitz, at sea level on the coast of Namibia. Here the mean annual rainfall is 23 millimetres. About 290 kilometres inland from Luderitz at Keetmanshoop, shown in Table 10.3, the mean annual rainfall is 166 millimetres. This higher rainfall results from the difference in altitude between the two places - Keetmanshoop is over 1000 metres higher on the Namibian Plateau. Arid and semi-arid areas in the lee of prevailing westerly winds from the sea include the Mojave desert and the Atacama desert.

6. Draw fully labelled cross-section diagrams in the same style as Fig. 10.4, to show the formation of:

(a) coastal fog and

(b) orographic rainfall and rainshadow.

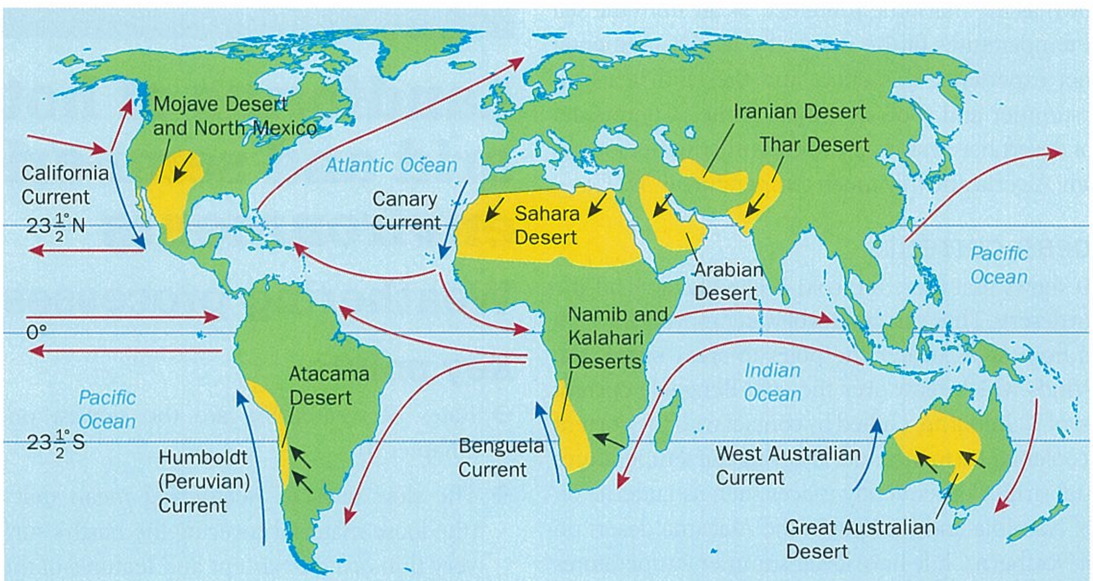

Fig. 10.10 The influence of ocean currents on hot arid and semi-arid climates

Temperature

Rain does not fall often in deserts but when it does it is usually torrential and often causes flash floods. This is particularly so on the parts nearest the Equator where occasional convectional storms occur in the summer heat. In these areas summer is usually the season when most rain falls.

Factors influencing the temperature in deserts

Latitude

The hot arid and some semi-arid areas experience overhead sun in summer, leading to extremely high temperatures. The sun is overhead at the Tropic of Cancer on 21 June and at the Tropic of Capricorn on 22 December, so it might be expected that these months would be the hottest for the hemisphere they are in. In fact, that is not usually the case, as there is normally a temperature lag as the heat builds up. The hottest month is usually a month later and the coolest month is usually a month later than when the sun is at its lowest in the sky at noon. In the tropical deserts the sun is never very low and so winters are normally hot and summers very hot. Also, away from the Equator the length of day is longer in the summer, giving more sunshine hours in areas without cloud to add to the heating.

Altitude

The air becomes thinner and contains less water vapour and dust to absorb the Earth's long-wave radiation, causing temperatures to decrease about 0.6 °C for every 100 metres of height gained (the environmental lapse rate). This contributes to the cooler temperatures at Keetmanshoop, Namibia.

Distance from the sea

As water heats and cools more slowly than land, coastal areas have warmer winters and cooler summers than places inland. This is known as the maritime influence, as air from the sea brings the temperatures of the sea to the land. Continental areas do not experience this effect and the land heats up quickly in summer and cools quickly in winter. Continental areas of hot desert have extremely hot summer temperatures (e.g. in Salah, Algeria, the July mean temperature is 37 °C).

Cold ocean currents

Fig. 10. 10 shows that there are cold ocean currents off the coasts of hot deserts. These are bodies of water moving through the oceans from areas nearer the poles to areas nearer the Equator. Winds which blow over the cold Benguela current off the coast of Namibia are chilled by contact with the current and carry cooler air on to the land, lowering the temperatures of the coastal strip. Consequently, places such as Luderitz on the coast of Namibia and Iquique in the Atacama desert on the coast of Northern Chile have lower summer temperatures than is expected for their latitudes.

Fig. 10.11 The Atacama Desert in northern Chile. In parts of this area rain has not fallen in living memory

Lack of cloud

Desert air has very low relative humidity so skies are often cloudless or have little cloud. This results in extreme diurnal temperatures. The maximum amount of solar radiation can reach the Earth's surface, so temperatures are often as high as 38 °C. In hot deserts they can reach over 50 °C in the shade in summer. At night, without clouds to stop the Earth's long-wave radiation escaping to space, temperatures drop to about 15 °C in summer and 5 °C in winter. Daily temperature ranges are very large all year round. Low night-time temperatures can result in the condensation of water vapour, forming dew, droplets of water on the surface. These are believed to be important in assisting weathering.

7. Study Tables 10.2 and 10.3 (see page 327) which show the climates of Luderitz and Keetmanshoop. Explain how the location of these places influences the differences in their climates.

Landforms of hot arid and semi-arid environments

Weathering processes

Key points

- Rates of weathering are the slowest on Earth (see Chapter 3).
- The slow rates of weathering mean that the regolith (the loose material covering the Earth's surface) is often very thin or non-existent and features of the underlying geology stand out clearly.

- Physical expansion and contraction due to the large diurnal ranges of temperature causes **thermal fracturing** (see Chapter 3).
- **Granular disintegration** leads to the development of sandy deserts (**erg**; see Chapter 3).
- Block disintegration leads to the development of bare rocks deserts (**hamada**) and stony deserts (**serir** or **reg**).
- **Exfoliation** occurs, probably assisted by chemical action.
- Chemical action is probably very slow due to the lack of moisture.
- **Salt crystal growth** is important (see Chapter 3).
- **Oxidation** of iron minerals colours the surface red. This is the main chemical process.

Exfoliation

This is the 'onion skin effect' where thick layers of rock peel parallel to the surface. Rocks are relatively poor thermal conductors, therefore when rocks are strongly heated during the day the heating and expansion are confined to surface layers which encourages the development of cracks parallel to the surface. During the cold nights the rocks contract and crack at right angles to the surface. The process is particularly effective on rocks such as granites and gneisses.

The effectiveness of this process has been questioned as sheet structures have been discovered below the depths of solar heating. The effects have also been attributed to pressure release jointing, salt crystal growth (see Chapter 3) or chemical weathering at depth. Experiments have been conducted to try to produce exfoliation in the laboratory. These have involved heating and cooling rocks many times to simulate many years in the desert climate. It seems that the process is only very effective when some water is present. This could be from the occasional rain shower or from dew which might produce a chemical effect or allow salt crystal growth.

The process often produces rounded, bare rock surfaces known as **exfoliation domes**.

Fig. 10.12 Exfoliation of rocks in Northern Cape, South Africa

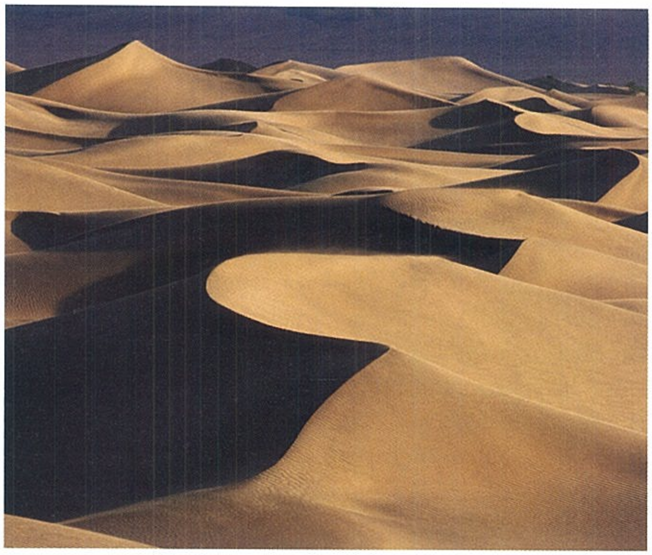

Fig. 10.13 A sandy desert, California, USA

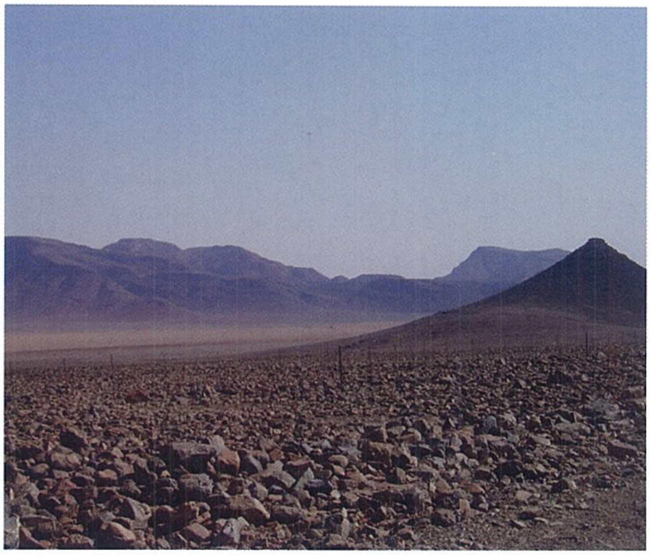

Fig. 10.14 A stony desert, Namibia

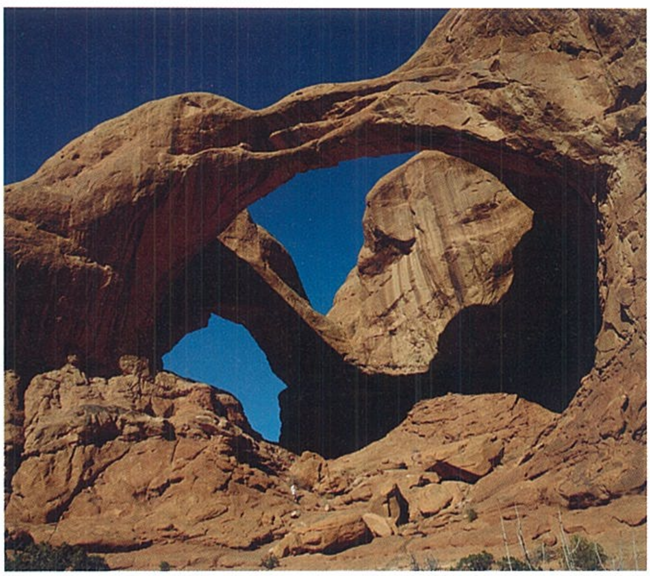

Fig. 10.15 A bare rock desert, Arches National Park, Utah, USA

Processes of erosion by wind (aeolian erosion)

Corrasion (abrasion)

Corrasion is the sand-blasting effect of the wind, exactly the same process that is used artificially to clean the surfaces of buildings. The wind picks up loose sand and hurls it against rock surfaces and the impact breaks away small fragments. The effect is greatest about 30 centimetres above the surface. This is because most blown sand is transported at this height. This means that isolated, standing rocks and cliffs tend to be undercut and form **rock pedestals** or 'mushroom rocks'.

Fig. 10.16 A rock pedestal in the White Desert, Egypt

Corrasion is a **differential** form of erosion. It attacks weaker layers and leaves more resistant ones. Where alternating hard and soft rocks are steeply dipping or vertical, differential abrasion can form **yardangs**. These are sharp keel-like ridges of rock separated from a parallel neighbour by a furrow. The ridges may be up to 6 metres high and 35 metres wide.

Fig. 10.17 Yardang field near the Dakhla Oasis, Egypt

Where alternating hard and soft layers lie horizontally, this may lead to the formation of tabular undercut hills called **zeugen** (singular zeuge).

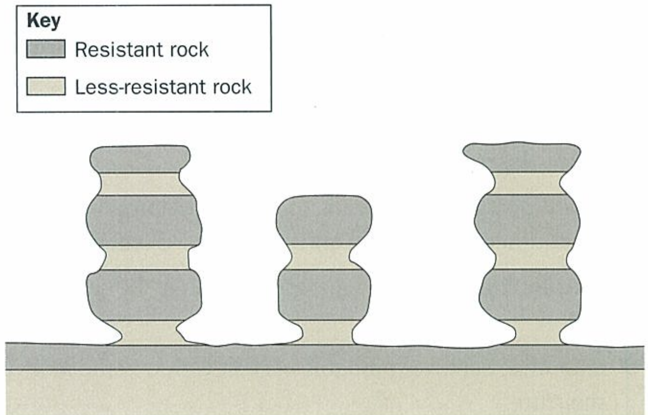

Fig. 10.18 Formation of zeugen

Pebbles and boulders in deserts often have a series of two, three or four surfaces (facets) which are worn and polished. These are referred to as **ventifacts** or dreikanter (three facets). They are the result of corrasion and the fact that winds in deserts tend to be concentrated from one direction. A surface is abraded, then if the stone is disturbed another surface is abraded. The surfaces may have a coating of **desert varnish**, a film of iron and manganese oxides deposited by evaporation of solutions brought to the surface by capillary action. Wind-faceted stones are also known in other climates, as Fig. 10.19 shows.

Fig. 10.19 Ventifact in basalt/dolerite, Wright Dry Valley, Antarctica

Deflation

Deflation is a process of erosion. It is the removal of dry, unconsolidated material (soil, dust, sand) from the surface. The finest material is carried high in the air and carried for many miles.

Deflation has two significant effects on the landscape:

- Different wind speeds are selective in the size of particle they pick up. The effect of this is to move lighter particles and to leave behind heavier ones. Large rocks are left to form stony deserts (**serir** or **reg**) and sand is moved elsewhere to form the great sand **erg**. Very fine particles may be blown outside the desert area and form soils in areas of more humid areas. The **loess** deposits in north-west China formed in this way. Deflation can result in major, enclosed depressions known as **deflation hollows**. One of these is the Qattara Depression (Arabic:

Munh˯afaḍ al-Qat̤t̤a¯rah) in north-west Egypt. The floor of the depression is below sea level and is covered with salt pans, sand dunes and salt marshes. In smaller but similar depressions 20 kilometres west of the Qattara Depression lie the oases of Siwa and Jaghbub. The Qattara Depression contains the second lowest point in Africa at 133 metres below sea level. The depression covers about 19605 kilometres^2. It is thought to form due to salt crystal growth (see Chapter 3) breaking down the rock, coupled with deflation removing the weathered debris.

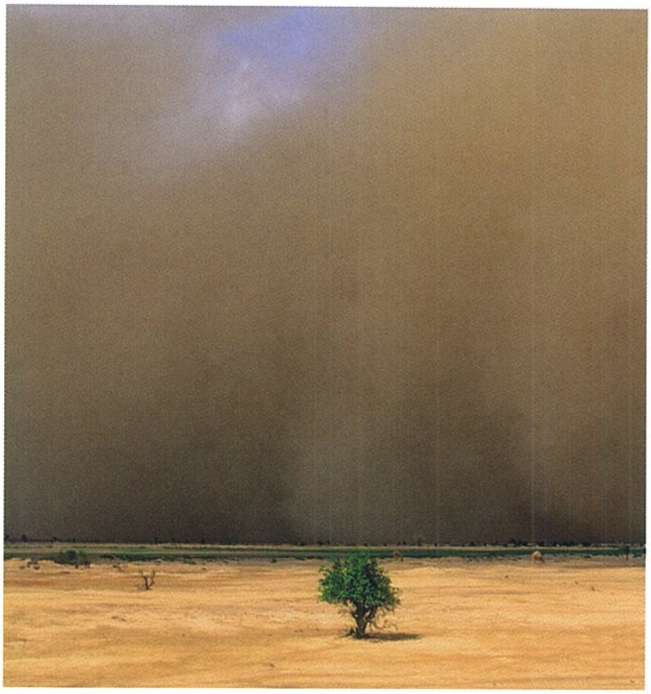

Fig. 10.20 A sandstorm in Mali

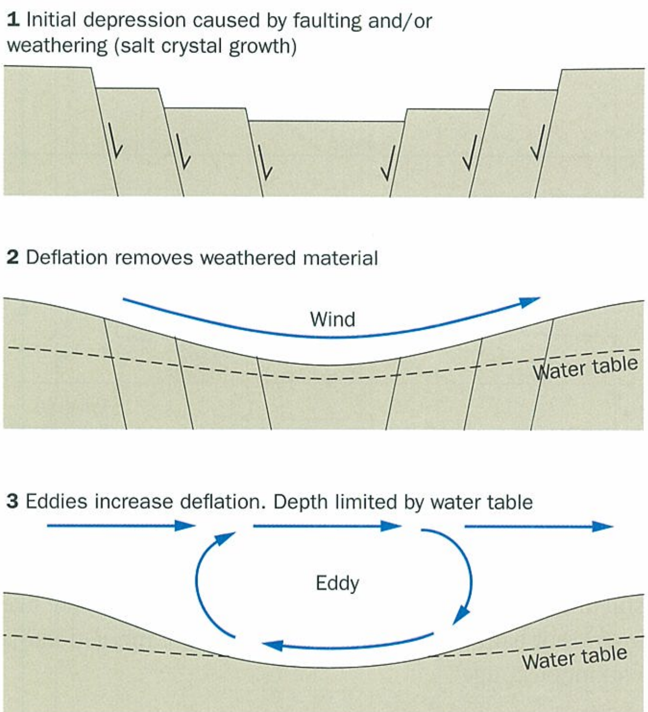

Fig. 10.21 Development of a deflation hollow

Some deflation hollows extend below the water table, forming oases. The rocks and sediment at the floor of the depression are saturated with water.

8. What is the water table?

9. Explain why the water table must limit the depth of deflation.

10. Explain how climatic change might play a part in the formation of major deflation hollows.

The other effect of deflation is on human activity. In major sandstorms normal life comes to a standstill and afterwards the deposited sand needs removing from roads, etc. Deflation is also the process involved in soil erosion by the wind, a significant process in semi-arid areas. For this to occur rainfall needs to be low so that the soil dries out and is loose and strong winds need to blow to remove the soil by deflation.

Deflation may be a cause of **oases** in deserts where the ground is excavated to the water table and water appears at the surface in the floor of the deflation hollow. However, there are other geological causes, particularly where **artesian effects** occur. Here the water table in mountains outside the desert is higher than the ground level within the desert. An aquifer, or water-bearing layer, is replenished or recharged by rain in the mountains. Where the aquifer runs beneath the desert, water may be forced up faults, forming elongate oases in the desert. Folding of the rocks may also bring the aquifer to the surface.

Processes of transport by wind (aeolian transport)

Sand-sized material (with particles of 0.04–2 millimetres) may be transported preferentially to smaller particles because it has a low shear velocity threshold; in other words the grains do not stick together. Larger particles are too heavy to lift. Desert winds are not necessarily stronger than other winds but the lack of vegetation makes them more effective in transporting surface material. **Saltation** is a process of transport. It is the main process by which sand is moved from place to place. In very strong winds, e.g. in sandstorms, sand may be suspended in the air, as are fine silt and clay-sized particles, but most winds do not have enough energy to do this and the sand moves along in the wind direction in a series of hops. This is a result of turbulence and variation in wind speed. Sand is constantly being picked up by stronger gusts and deposited in more calm conditions. The impact of grains landing on others may push other grains along. The moving carpet of grains is concentrated in the first 30 centimetres above the ground. At low wind velocities sand can be moved by **creep** where it is pushed forward without leaving the surface.

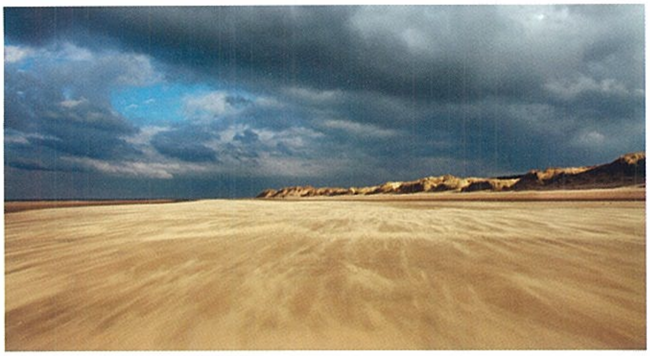

Fig. 10.22 Saltation at work

Fig. 10.23 A barchan dune. The slip face is in shadow. The wind direction is from left to right

Deposition by wind

Material transported by saltation or suspension is deposited when the wind speed drops and energy is lost or in sheltered spots such as the lee of dunes and boulders. A reduction in the shear velocity of the wind is needed and the grains then fall out of the transporting wind and are deposited on the surface. Obstacles such as rocks or plants may trigger grains being deposited on their sheltered, lee sides. Shear velocity may also be affected by the roughness of the desert surface, depending on the nature of the rocks or boulders present. Once a patch of sand develops, it can grow by trapping more sand in its lee and may grow into a dune.

Sand dunes

Sand may be produced by marine erosion, fluvial erosion, aeolian erosion and weathering (granular disintegration). As already described, it is then transported and deposited by wind to areas where it accumulates. Dunes have complex forms, but a simple classification is in terms of their orientation to the wind.

Barchans

These are crescent-shaped dunes which develop transverse to winds which have a strong tendency to blow from a single direction and where there is a relatively limited sand supply. They occur in large 'swarms' and are common in North Africa, Namibia and Peru. The features of **barchans** are shown in Fig. 10.24.

On an initial accumulation of sand, the wind causes sand to saltate up the gentle windward slope then avalanche down the steep leeward slope, achieving its maximum angle of rest (often about 32°–34°). As the wind blows up the windward slope, streamlines are compressed, increasing the wind speed and erosion. Beyond the crest, streamlines are decompressed, velocities decrease and deposition occurs. Vortices (eddy currents) may steepen this slope. This transfer of sand from windward to leeward causes the dune to move forward. There is less sand at the margins; therefore, the horns move forward faster than the rest of the dune, until shelter from the dune slows their advance.

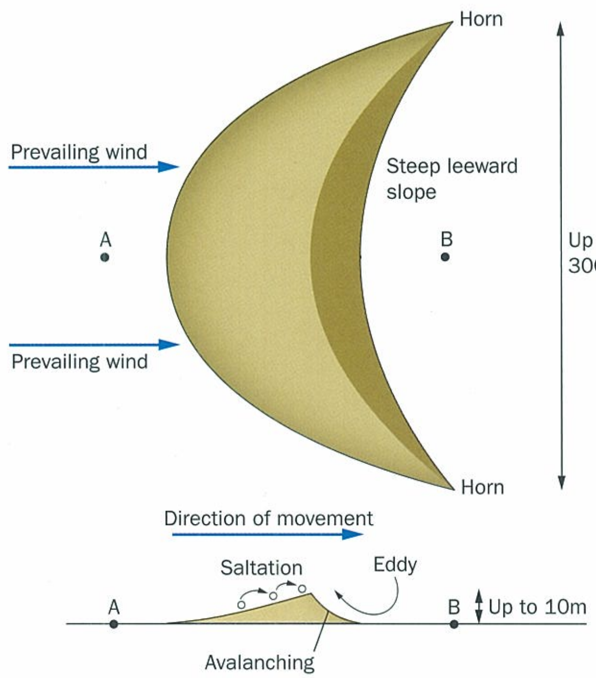

Fig. 10.24 The features of a barchan dune

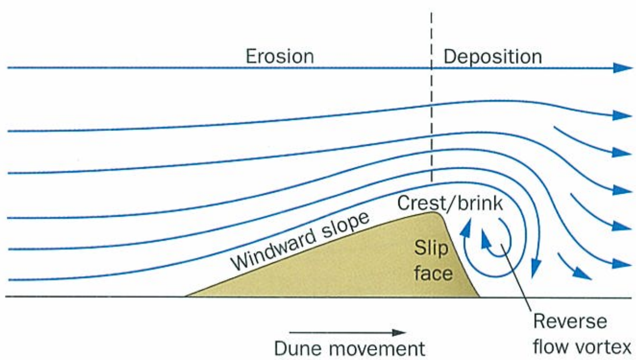

Fig. 10.25 The compression and decompression of wind streamlines over a barchan

Where there is an abundant sand supply but the winds are still unidirectional, barchanoid ridges develop. They are like a series of barchans the horns of which have merged into a continuous ridge.

Seifs

Fig. 10.26 A seif dune, Sossusvlei, Namibia

Seifs are linear dunes which lie parallel to the main wind direction. They develop where there are winds from two directions and a relatively limited sand supply. The linear ridges can be up to 200 metres high and over 1 kilometre apart. They have sharp crests and steep sides with slip faces.

These dunes appear to trap sand from two directions, with slip faces possible on either side. They extend in the resultant direction of the two winds.

Star dunes (mega-dunes)

These very large dunes develop where there are complex winds and a large supply of sand. There is a central peak with radiating arms, each arm corresponding to a different wind direction. The dunes can be up to 400 metres tall and there is no overall lateral movement. They occur in the central Sahara, Namibia, China and Iran.

Parabolic dunes

These are barchans where the horns have become fixed by vegetation. The central part of the dune moves forwards but the horns are fixed so that, unlike barchans, the horns face up wind.

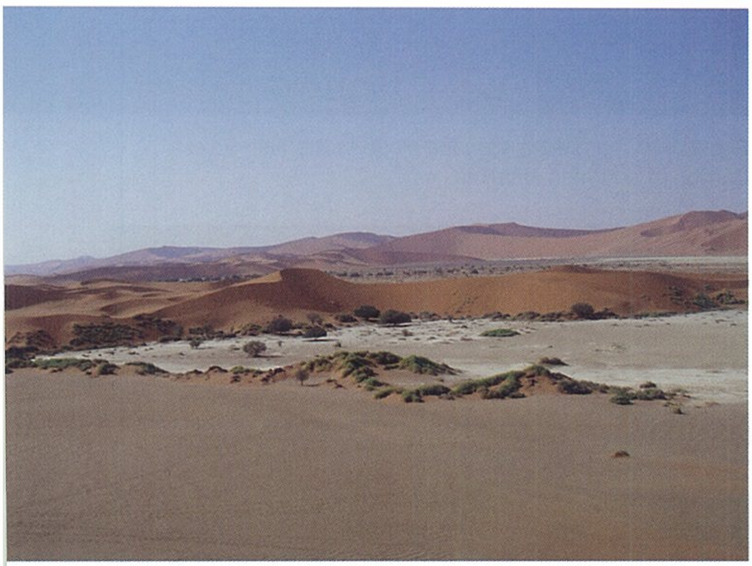

Fig. 10.27 Dunes fixed by vegetation, Sossusvlei, Namibia

Echo dunes

These form in the sheltered lee of hills. They can be fairly stable and sometimes vegetated.

Dune management

Moving dunes can swamp houses, roads, oil installations and oases. Old vegetated dunes can be reactivated if the vegetation is removed by farming, drought or fire. Dunes can be managed by controlling grazing, use of fences, planting vegetation or even by removal of the dunes.

11. List the factors which can cause deposition by the wind.

12. Explain the factors which cause desert sand dunes to have different forms.

Processes of erosion, transport and deposition by water

The pattern of **episodic rainfall** described earlier where rainfall, especially in hyper-arid areas, may occur in a torrential storm every few years, leads to rivers with very unusual **hydrological regimes**.

Semi-arid areas, e.g. the Sahel on the south side of the Sahara, with boundaries with the savannas may experience summer rainfall and therefore **seasonal rivers** may develop during this season. In contrast, semi-arid areas, e.g. parts of the Maghreb, with boundaries with the area of Mediterranean climate may experience winter rainfall and have seasonal rivers during this season. Where the climate is drier, streams are **intermittent** rather than seasonal. Rivers with sources outside the arid area, e.g. the Nile in North Africa or the Orange in southern Africa, are **perennial** and are described as **exogenic rivers**.

The torrential, episodic rainfall tends to produce **flash floods**. Rainfall intensity exceeds the infiltration rate and overland flow occurs. Run-off from the sparsely vegetated surfaces is rapid. This produces dangerous, sudden but short-lived floods in usually dry valleys. There is an abundance of weathered material on the surface and the stream may turn into a mudflow. The mudflow contains material from clay-sized particles to boulders and, when flowing rapidly, has great erosive force. Large quantities of sediment are moved in short time periods. This is an example of a geomorphological event with a low frequency but a high magnitude. Flash floods are highly dangerous to people and property. The short-lived rainfall and high evaporation rates mean that the flash floods soon dry up.

Many intermittent and seasonal rivers do not end in the sea but lie within **inland drainage basins**. These basins are particularly common in tectonically active areas, e.g. the basin and range topography of western USA. Some of these can be very large, e.g. the basins centred on Lake Chad in Africa or the Okavango Delta in Botswana.

Where overland flow occurs on relatively gentle slopes, the water does not become concentrated in channels and this results in a **sheet flood**. These also cause erosion and are why even the most gentle of hillsides in semi-arid areas are often terraced.

Fig. 10.28 Contour ploughing in a dry area in South Africa

Where slopes are slightly steeper, a fine network of channels known as **rills** may develop. These may coalesce into larger **gullies**. On steep slopes **stream floods** rather than sheet floods are the norm.

Fig. 10.29 An aerial view of the Valley of the Kings on the west bank of the river Nile near Luxor, Egypt

13. A flash flood is described as an example of a geomorphological event with a low frequency but a high magnitude. Explain this statement.

14. Draw a fully labelled sketch map of a world example of an inland drainage basin.

Past climate change

Anyone flying at 10 000 metres above the Sahara will see the expected desert features such as sand dunes. In addition, they will see obvious signs of water action such as extensive dendritic (tree-like) patterns of wadis and valleys. Some of these features can be explained by the sporadic nature of desert rainfall but some have been eroded during periods of much wetter climates in the past. In fact the distribution of deserts has changed significantly over time. This has been caused by astronomical factors such as changes in patterns of the Earth's orbit, uplift of mountain ranges, changes in the positions and configuration of the land masses (continental drift), changes in the water circulation deep in the oceans and the development of ice sheets (glaciation).

Fig. 10.30 A desert landscape close to the Fish River Canyon in southern Namibia

15. Study the desert landscape shown in Fig. 10.29. Describe the evidence in the photograph for the effects of running water. Has running water occurred in the recent past? What is the evidence?

Evidence for climatic change

Landforms and deposits

- Vegetated sand dunes in the Kalahari, a semi-arid area, indicate previous drier climates.

→ Old lake beds, lake sediments and river channels indicate previous wetter climates.

Archaeological evidence

→ Rock paintings in the Sahara show animals such as elephants and indicate past, wetter climates.

→ Archaeological evidence shows that human populations in Africa have fluctuated and that, in wetter periods, areas which are now desert were once inhabited. Africa's population was probably at its lowest during a very dry period about 70 000 years ago.

Faunal evidence

→ The evolution of the horse in the Tertiary period in North America coincides with the development of a drier climate and the consequent development of grassland.

Ocean sediments

→ The ratio of the oxygen isotopes O^{16} and O^{18} in the skeletons of micro-organisms on the ocean floor gives a precise indication of ocean temperatures in the past. However, it is not easy to say how these water temperatures relate to air temperatures and the development of ice sheets and aridity.

→ During periods of dry windy climate, sand was blown out of the deserts and into the oceans. This sand is found in cores of ocean floor sediment.

Ice cores

→ Ice cores are cylinders of ice drilled out of an ice sheet or glacier. The oldest continuous ice core records to date extend back 123 000 years in Greenland and 800 000 years in Antarctica. The ice encloses small bubbles of air that can be used to measure the past concentration of gases (including carbon dioxide and methane) in the atmosphere. Warmer climates are associated with higher CO_2 values and colder climates with low CO_2 concentrations. CO_2 is a positive feedback mechanism and amplifies changes in temperature. Global changes in temperature cause changes in aridity, as described below.

Patterns of aridity in the past and the development of modern deserts

Miocene

The origin of many of the modern deserts appears to date from this epoch, with increased aridity in continental Australia, Asia, Africa and the Americas. In the southern hemisphere, the Antarctic ice sheet developed, the Southern Ocean cooled and the cold Benguela current formed. The cooler air was less capable of holding moisture. In addition, Australia drifted northwards to its present position in the horse latitudes of high pressure and descending air.

Period		Epoch	Millions of years before present
Quaternary	Neogene	Holocene Pleistocene	0
Tertiary		Pliocene	2.6
		Miocene	5.3
	Palaeogene	Oligocene	23.0
		Eocene	33.9
		Palaeocene	55.8
			65.5

Table 10.6 The time scale of the Cenozoic Era. Today is at the top of the table

The uplift of the Himalayas and Tibetan Plateau blocked penetration of moisture-bearing, south-westerly monsoon winds into central Asia, leading to the development of the mid-latitude Gobi desert and the surrounding semi-arid steppes.

In Africa the tropical easterly jet stream became stronger, bringing dry stable air to the Sahara. In the area north of the present Sahara, there was an ancient sea, the Tethys Sea. This sea closed up during the Miocene epoch, increasing the **continentality** and aridity of North Africa.

In North America, the uplift of the Sierra Nevada and Transverse Ranges of southern California caused a barrier to moist air from the Pacific and led to the formation of the Mojave and Great Basin deserts. Westerly, moisture-bearing winds were less likely to reach the area from the Pacific Ocean and local areas of rainshadow developed. Further north, the uplift of the Rockies caused increasing aridity on the Great Plains, resulting in the development of grasslands and the evolution of the horse, an animal adapted to this environment. The uplift of the Andes in South America had a similar effect on the development of the Atacama desert and Patagonian grasslands.

The ice ages and 'Pleistocene pluvials'

During the past million years, the Earth's climate has oscillated between glacial and interglacial periods. There were as many as 11 glacial phases. During the glacials, there was global cooling and ice sheets developed over the poles. In the interglacials there was global warming and the ice sheets retreated. The patterns of global pressure and winds changed and had an effect on the deserts, changing their extent and degree of aridity. Opinion as to how this mechanism works has changed over the years.

In 1868 Taylor used the term **pluvial** to indicate a period of increased moisture availability, generally due to increased precipitation but also related to lower evaporation. It was believed that there was a simple relationship between the pluvials and the glacial fluctuations in the northern hemisphere. It was thought that during glacials the climatic belts simply moved south so that the deserts were wet. During interglacials (like today) the deserts were dry. However, more recent studies show that a simple glacial period = pluvial period theory cannot be applied to all areas.

If the present day deserts were once wetter, it is possible that, at the same time, areas nearer the equator were drier than they are today. In both hemispheres the areas of land ice and sea ice increased. This in turn increased the areas of polar high pressure and displaced the zone of mid-latitude cyclones to lower latitudes, making the present day deserts wetter. In Africa the inter-tropical convergence zone (ITCZ) was displaced hundreds of kilometres southwards, leading to the failure of the onshore, south-westerly monsoon winds, greater development of offshore trade winds and increased aridity over much of the continent. During this period the River Nile is thought to have hardly flowed at all.

During the Pleistocene period there were periods of climate that were both drier and wetter than today. In drier times marginal desert areas such as the **Sahel**, Kalahari and parts of Australia were much more arid than today. The Sahara may have advanced southwards 500 kilometres along its southern front from Senegal to Ethiopia. Lake Chad disappeared. The upper Nile became an area of inland drainage. The Kalahari extended northwards almost to the mouth of the Congo. These areas have dune systems now covered by savanna vegetation. Fossil dunes in the Great Plains of North America also date from this period.

In the wetter periods the area of the deserts shrank, although the core hyper-arid areas of the central Sahara and Namib were unaffected. In North America cyclones from the Pacific Ocean were steered further south, resulting in increased precipitation and the development of Lake Bonneville and a lake in Death Valley. Parts of the Sahara were inhabited before the glacial maximum. In 2013 a team of researchers from Germany and the UK found evidence of three major river systems that may

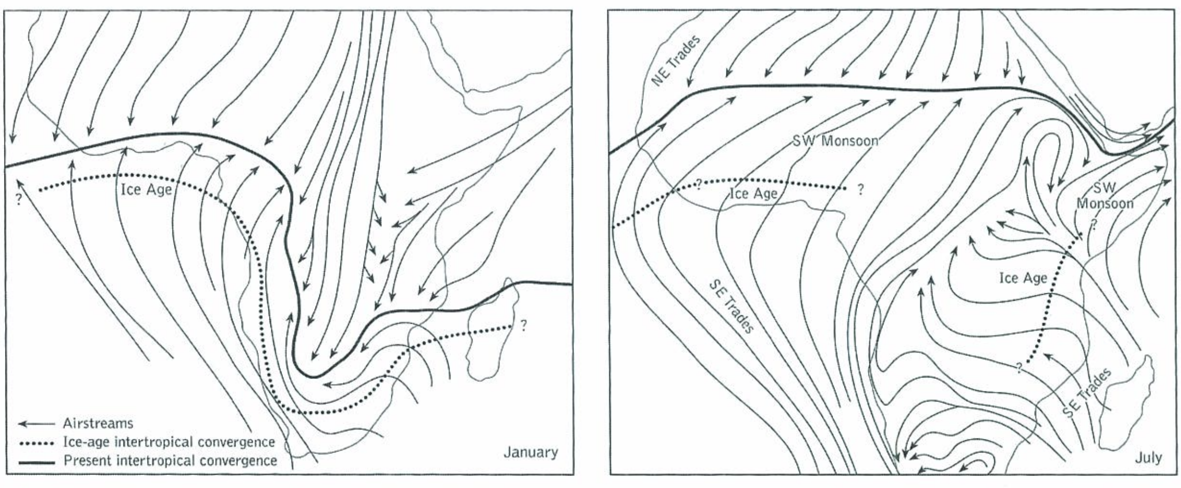

Fig. 10.31 The present position of the winds and inter-tropical convergence zone in Africa and how the pattern might have been during an glacial phase 18 000 years ago

have existed in the Sahara about 130000–100000 years ago, but are now largely buried by dune systems.

Some of the most impressive evidence of climatic fluctuation comes from the **pluvial lakes**. These are lakes which have experienced large fluctuations in volume due to changes in rainfall and evaporation. Pluvial lakes have been used to interpret palaeoclimates (ancient climates). Ancient shorelines seen as landscape features can be mapped to show the previous extent of lakes. The former lake beds are also shown by the saline deposits, algal limestones, marls and clays deposited on the lake bed (see the later section on playa lakes).

Lake Bonneville in south-west USA has been studied in great detail and several former shore lines have been mapped. The present day lakes (Great Salt Lake, Utah Lake and Sevier Lake) represent 5 per cent of its former size. At its greatest extent, 32 000 to 14 500 years ago, Lake Bonneville was 330 metres deep and covered and area of 51 000 kilometres^2. Lake Chad (in Africa) is another of the largest pluvial lakes ever known and reached its maximum extent at about 5 000 BCE.

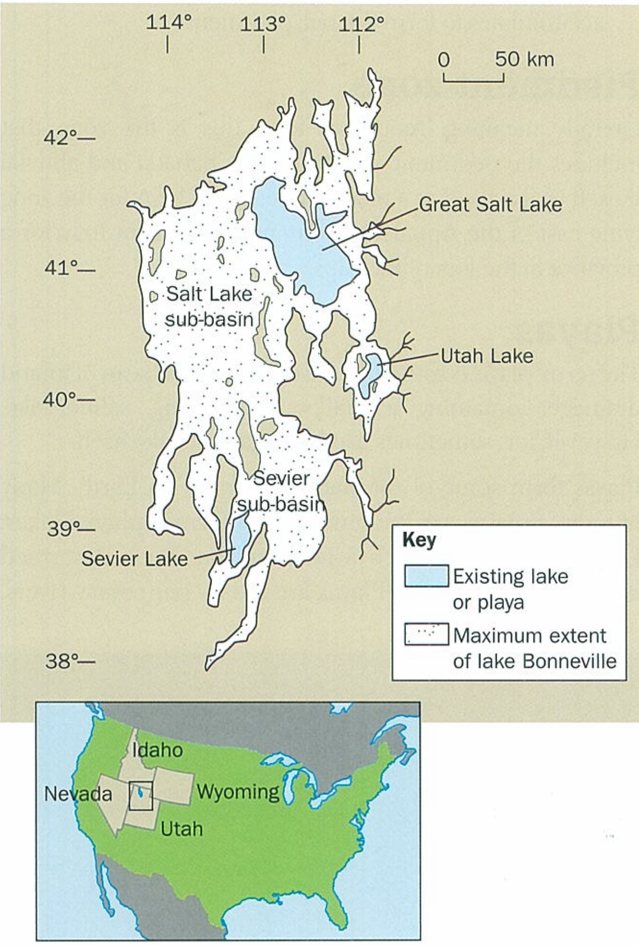

Fig. 10.32 Lake Bonneville and its remnant lakes, Utah, USA. Some of the present lakes are salt flats and not covered by water. The salt flats have been the scene of many attempts on the world land speed record

Fig. 10.33 Lake Bonneville Salt Flats, Utah, USA

Since the ice ages

After the last glacial period some of today's semi-arid areas became wetter, e.g. leading to development of savanna vegetation on dunes in the Kalahari. Lake and spring deposits, faunal evidence and archaeological evidence indicate wetter conditions in Africa between 9000 and 6000 years ago.

Much of the change since the warming began 18 000 years ago has been related to changes in the circulation of water in the deep oceans. In the past 14 000 years droughts in the Sahel and tropical Mexico coincide with injections of fresh water into the North Atlantic Ocean. Circulation slowed and colder surface waters resulted in less evaporation and therefore reduced precipitation in the surrounding land masses. Colder, fresher water correlates with a southward shift of the tropical rain belt and drier conditions in West Africa.

Today

The possible spreading of the deserts is referred to as **desertification** and is described later in this chapter.

16. What is the evidence for past wetter climates in the Sahara and past drier climates in the Sahel and Kalahari?

Wadis and arroyos

These two terms are often used to mean the same thing. A **wadi** (Arabic) is a steep-sided, rocky ravine or valley in a desert or semi desert which is usually dry. Wadis contain features of upper course river in humid lands; they may show interlocking spurs or dry waterfalls. An **arroyo** (Spanish) is a stream bed which is usually dry except during flash floods. The term is often used in Latin America and south-west USA.

Wadis are the result of rapid vertical erosion during short-lived flooding. Erosion is rapid because of the power of the flash flood which, in turn, is a result of the high discharge of water and the large load carried (see the previous section). The lack of weathering means that the valley sides maintain their steepness.

Alluvial fans and bahadas

Alluvial fans are cones of debris found at the foot of mountains. They are not restricted to arid climates, although they are characteristic features of them. They are made up of coarse sand, gravel and large cobbles which form a gentle surface slope (usually less than 10°) away from the mountains. The temporary rivers on the fan show braided patterns.

When a flash flood emerges from a mountain valley on to the surrounding plain, deposition is triggered by:

- the sudden drop in gradient and energy
- the lateral spreading of the water
- evaporation rapidly causing the river to dry up completely
- water percolating into the earlier, highly permeable gravel deposits.

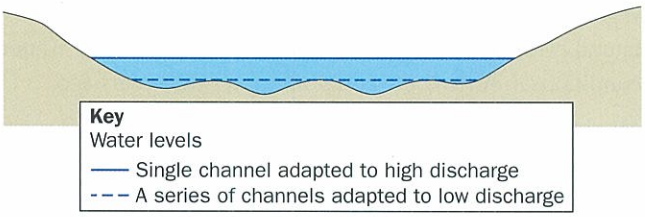

Fig. 10.34 Cross section of braided channels

Over time the deposits accumulate to form the characteristic fan shape. Braided streams develop as a normal response to large fluctuations in discharge, so that the channels are efficient whatever the flow.

Bahada (anglicised from the Spanish *bajada*) is a continuous gently sloping fringe of scree, gravel and coarse sand along the base of a mountain range in a semi-arid area. It has been formed by the coalescence of a series of alluvial fans.

Pediments

A pediment is a gently sloping (maximum 6° or 7°) rock platform, either bare or with a thin covering of rocks which stretches away from the foot of a mountain range. The upper edge often forms a sharp angle with the mountain front, although it may be covered by bahada deposits. It may dip beneath a thicker covering of peripediment deposits.

Pediments are found in south-west USA and in the arid lands of southern Africa. Sometimes the thin covering of rocks is cemented together in a pavement.

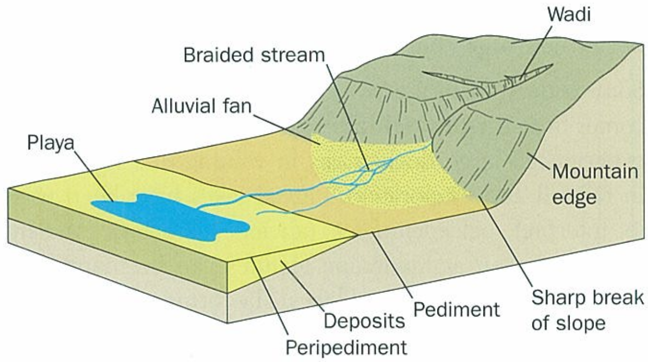

Fig. 10.35 Landforms in an inland basin of drainage in a semi-arid area

There are two theories about the origin of pediments.

- During episodic rainstorms, lateral erosion by streams, sheet floods and rills produces the sloping plains.
- The steep, mountain front retreats parallel to itself due to weathering and erosion, extending the pediment. This maintains the slope angles of the mountain front and the pediment. Weathered material is carried from the mountain front across the pediment where it finally accumulates to form the peripediment.

Piedmont zone

Literally meaning 'mountain foot', this is the zone that includes the pediment, peripediment, bahada and alluvial fans. It is also used as a place name: in the USA for the zone lying east of the Appalachian mountains and in Italy for a province at the foot of the Alps.

Playas

The term 'playa' is sometimes used to mean a basin of inland drainage containing a shallow, fluctuating, saline lake. However, it is sometimes used to mean the lake itself.

Playas form some of the flattest surfaces on Earth. Many of today's playas are the remnants of former pluvial lakes; Lake Bonneville is such a lake and has been described earlier in this chapter. Playas are fed by temporary rivers.

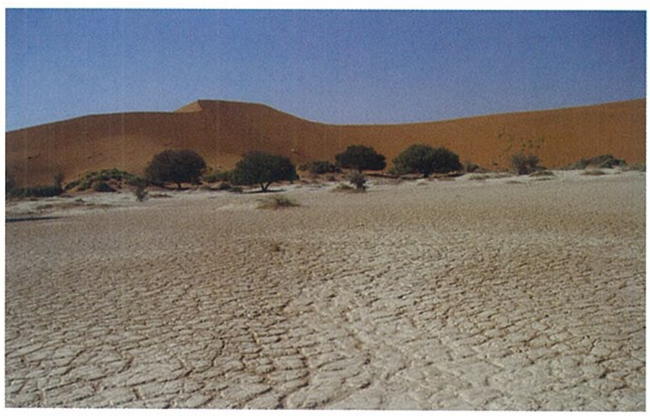

Fig. 10.36 Desiccation cracks forming on a salt crust of a playa in Namibia

Normally these rivers will have deposited their coarser load before reaching the playa, e.g. in alluvial fans. Only silt, clay and solutions are carried by rivers to the playa. The salts are the products of weathering of the surrounding rocks and are transported to the playa where evaporation results in their crystallisation. The lakes have extremely high salinity levels. Extensive salt crusts often surround any remaining water. Desiccation cracks are common features.

The salts are mostly halite (sodium chloride), although gypsum (calcium sulphate), calcite (calcium carbonate) and other salts may occur. Sometimes the salts may be of commercial value, e.g. saltpetre (potassium nitrate) and Chile saltpetre (sodium nitrate), used in the manufacture of fertilisers and explosives respectively.

Inselbergs

The term 'inselberg' comes from the German for 'island mountain' and means an isolated upland. Although there are different theories about the origin of inselbergs, they are all based on the concept that the isolation is due to erosion and that inselbergs are *residual* hills, in other words they are remnants of former landscapes or land. Inselbergs come in various forms:

- Flat-topped inselbergs occur in horizontal sedimentary strata where resistant cap rocks protect the weaker layers below from erosion. Larger masses are referred to as **mesas** (Spanish for 'table') and slimmer ones as **buttes**. They form the landscapes of much of southern Africa but also the scenery of Zion National Park, Utah and Monument Valley, Arizona, USA, made famous by old movies and US nuclear tests.
- Domed inselbergs are called **bornhardts**. They rise abruptly from the plains and often form in coarsely crystalline granites and gneisses. Uluru (Ayers Rock) in Northern Territory, Australia is an example, although in this case the rock type is sandstone.
- The **kopje** of the African plains are piles of granite boulders resting on bedrock which occur on hilltops. They may represent the last stages of the destruction of an inselberg by erosion.

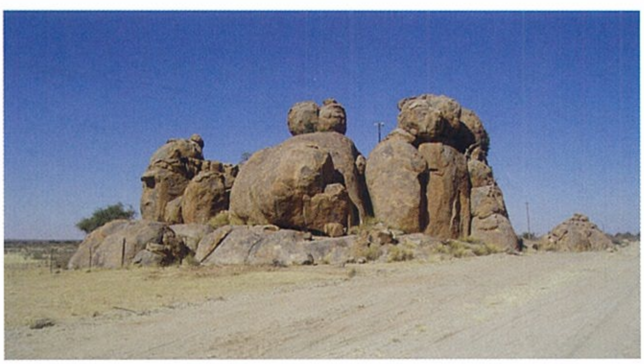

Fig. 10.37 A typical tropical kopje, Namibia

The origin of kopjes has been the topic of a whole series of academic discussions over many years. It is beyond the scope of this book to review these debates. It is possible that they may have formed in past wetter climates which allowed deep chemical weathering of the rocks. This may have been followed by erosion which removed the loose, weathered material. This is illustrated in Fig. 10.39.

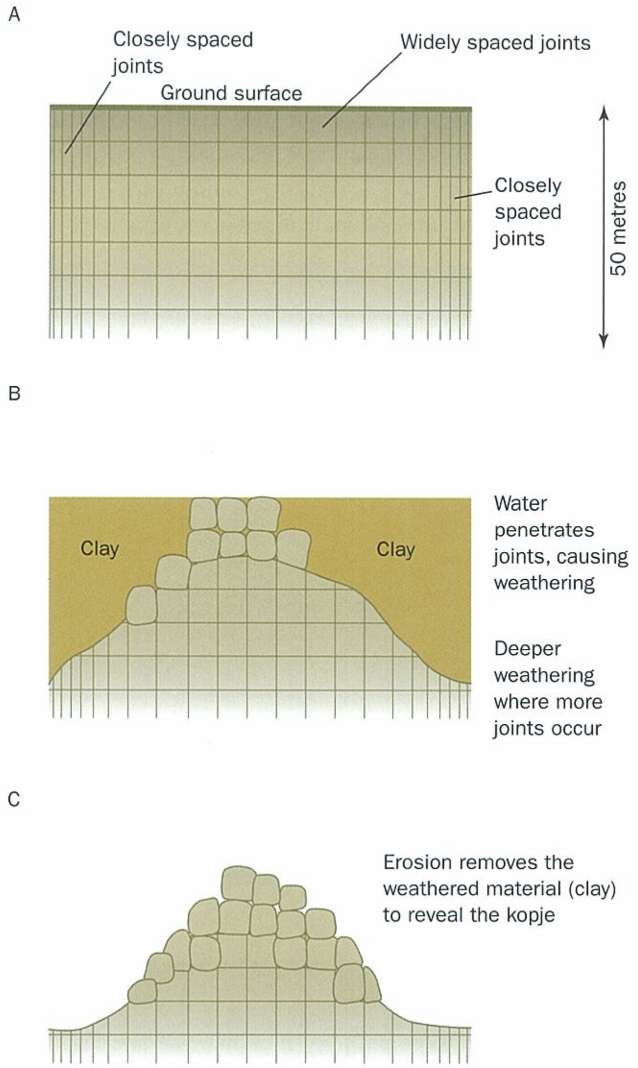

Fig. 10.38 The role of chemical weathering and erosion in the formation of kopjes

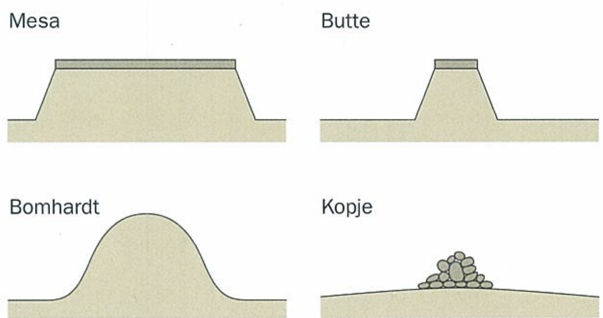

Fig. 10.39 The different forms of inselbergs

Inselbergs are common in the tectonically stable shield areas of southern Africa, the Arabian peninsula and Australia. In these areas weathering and erosion have gone on for long periods and produced extensive plains such as the Bushmanland Surface of Namaqualand and Namibia. Erosion may have been going on since the Palaeogene (see Table 10.5 on page 334) or even earlier in the Cretaceous period.

The importance of joint spacing in weathering and the development of the landscape has already been discussed. This has been important in the development of bornhardts and kopje, although in some cases they may be exposed intrusions or faulted features. The fact that the rock of bornhardts is generally the same rock as the surrounding plains supports the view that they are residual features of erosion.

Fig. 10.40 Mesas in Namibia

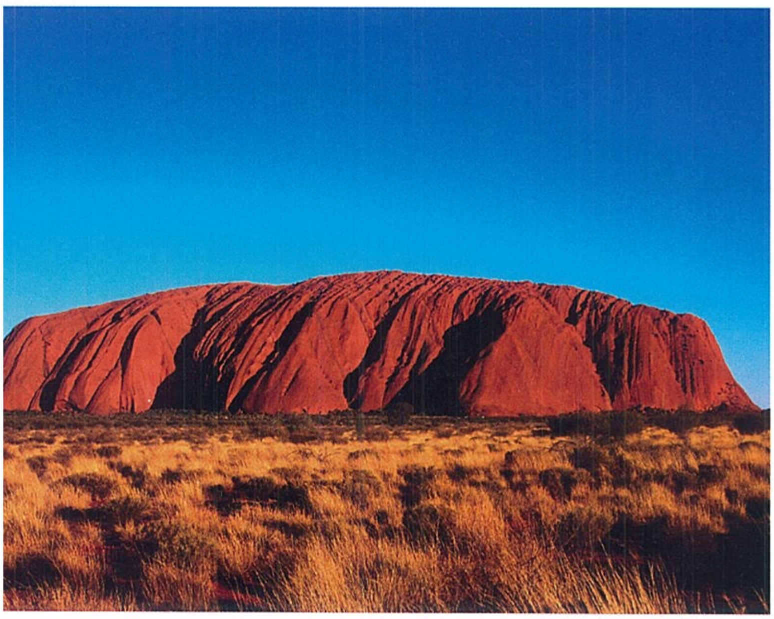

Fig. 10.41 Uluru (Ayers Rock), Northern Territory, Australia

Fig. 10.42 Monument Valley, Arizona, USA. Notice the slender buttes on the left

Landscapes with distinct slope elements such as plateaux, escarpments, bahadas and pediments are common in much of southern Africa. They often develop in horizontal strata with resistant cap rocks. They contrast with the convexo-concave landscapes found in some humid temperate areas. They lead to the idea that steep slopes will retreat parallel to themselves and will only become gentle when two gentle slopes at the base finally meet. This process assumes initial rapid uplift to trigger vertical erosion (rejuvenation) followed by long periods of stability when the steep slopes retreat.

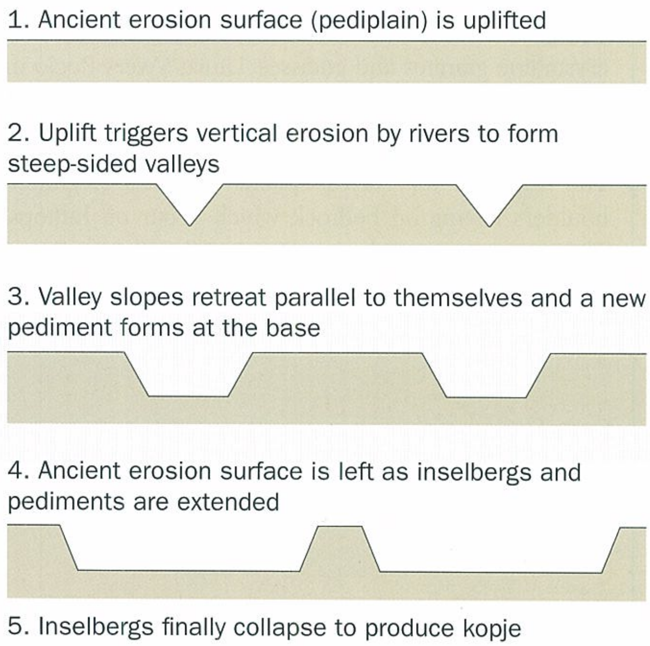

Fig. 10.43 A diagrammatic representation of the development of pediments and inselbergs through slope retreat

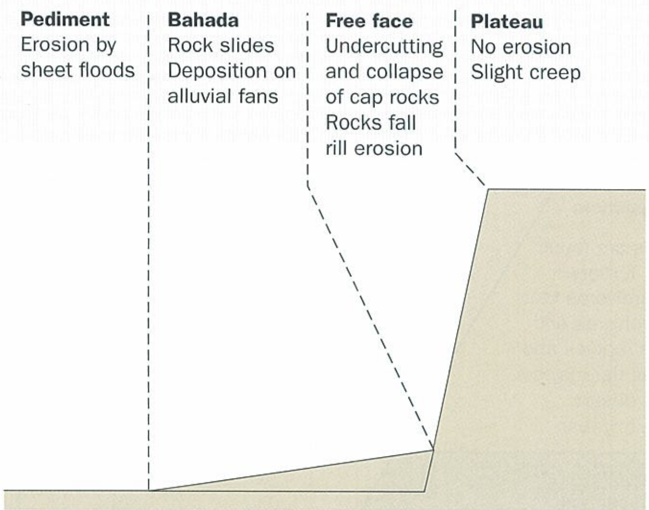

Fig. 10.44 Weathering, mass movement and erosion processes in a semi-arid landscape

17. Describe the processes, both on and beneath the surface that might lead to the development of pediments and inselbergs.

18. In this chapter the climatic changes experienced by deserts have been described. These changes have influenced landform development. Using the section on weathering in Chapter 3, describe the landscape shown in Fig. 10.45 and explain how past climates may have influenced its development.

Fig. 10.45 A landscape in the Namib desert, Namibia

Soils and vegetation

Biomass productivity

Biomass is the total amount of living matter in a given area. Moisture availability and temperature influence the rate of production of organic matter. In deserts, the fact that potential evapotranspiration rates greatly exceed precipitation means that biomass productivity is low compared with other zones.

Biome (global ecosystem)	Net primary production (g/m^2/year)	
	Range	Average
Desert and semi-desert	0–250	40
Artic and alpine tundra	10–400	140
Coniferous forest	400–2000	800
Deciduous forest	600–2500	1250
Grassland	200–1500	600
Tropical forest	1000–3500	2200

Table 10.7 Net primary production in some major biomes. This is a measure of the rate of production of organic matter by plants and animals

An ecosystem consists of a community of living organisms and its physical environment. The non-living (abiotic) components of an ecosystem include air, water and soil. Energy and nutrients flow through the system. Matter and energy are continually moving from the physical environment through living things and back into the physical environment. Trophic structure is the pattern of movement of energy and matter through an ecosystem. The plants and animal community are classified into a number of trophic levels.

In a biomass pyramid each tier represents the total dry weight of all species - grams/square (g/m^2) - in each trophic level. Most such pyramids narrow sharply from producers at the base to the consumers at the top level. A pyramid represents trends in food consumption, with the lowest level (primary producers) having the greatest total biomass, and the higher consumer levels having successively less total biomass.

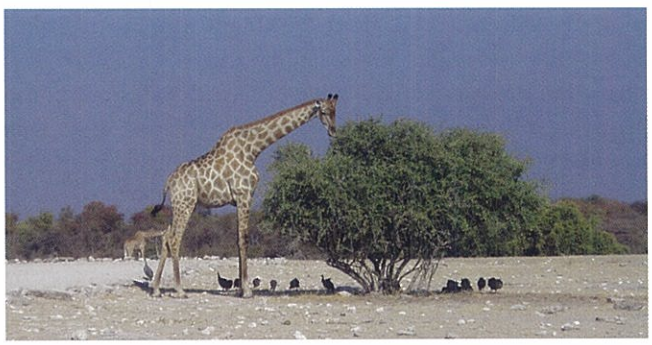

Fig. 10.47 Giraffe and guinea fowl in Namibia. Both are primary consumers

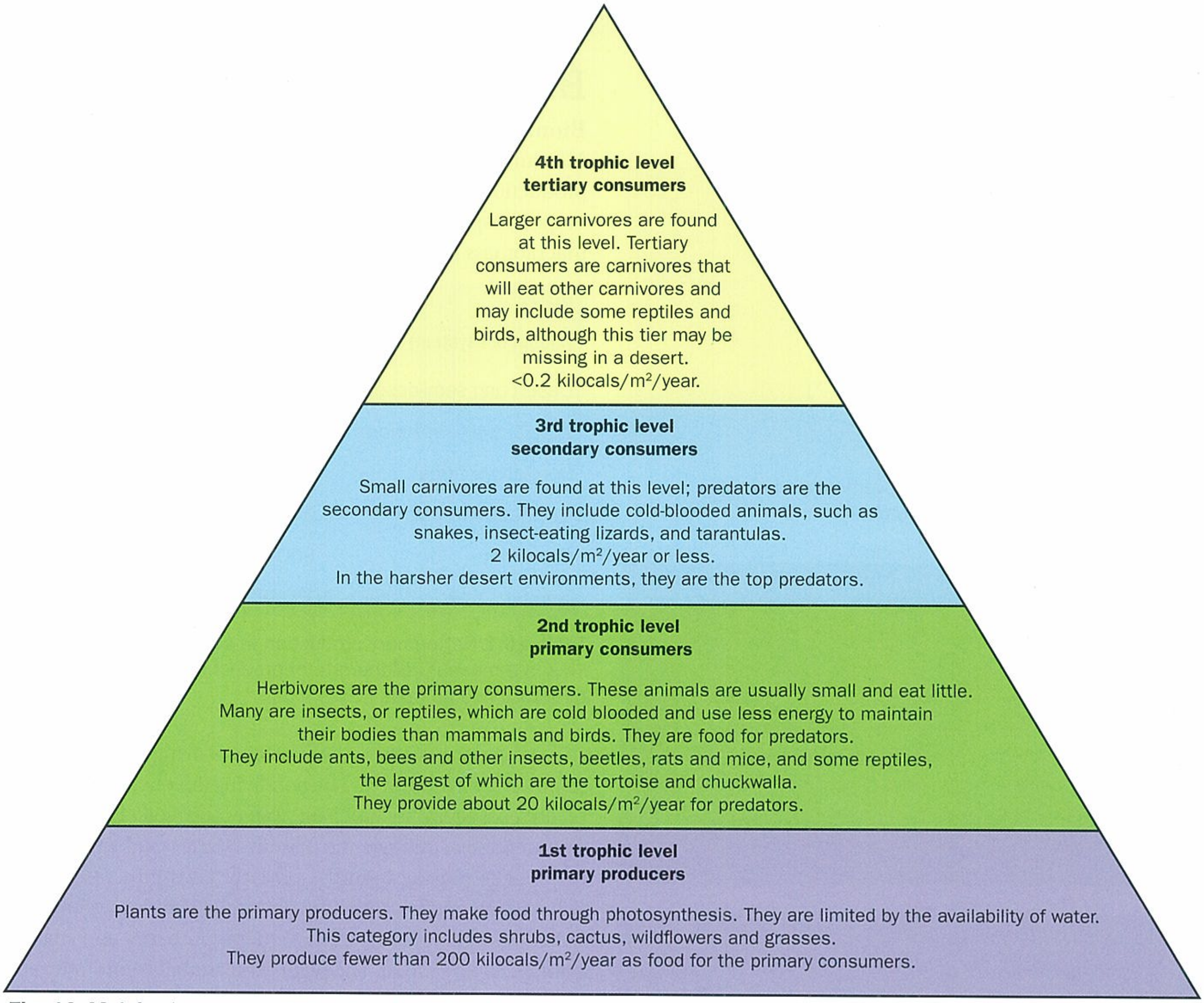

Fig. 10.46 A food pyramid in hot arid and semi-arid areas

Biodiversity

Many plants not only survive but thrive in the harsh conditions of the arid and semi-arid areas. Few areas are completely barren and those areas which receive some rainfall have a diverse flora. Although drought resistant plants are the rule, water-loving plants (hydrophytes) occur around oases. Arid and semi-arid flora and fauna are relatively species-poor, despite the diverse life forms found in deserts. Arid vegetation is increasingly sparse, open and discontinuous as aridity increases.

For example, in the Sonoran desert (semi-arid) of south-western USA 60 mammal species, 350 bird species, 20 amphibian species, over 100 reptile species, 30 native fish species, over 1000 native bee species and more than 2000 native plant species have been recorded. The Sonoran desert area south-west of Tucson and near the Mexican border has the only population of jaguars living within the USA. The Sonoran desert's twice yearly rainfall pattern results in more plant species than in other deserts. The Sonoran desert includes plant genera and species from the agave family, palm family, cactus family, legume family and numerous others, including the examples listed in Table 10.7.

Deserts may have a large ecosystem diversity - the variety of landscapes found together in any region, and the ways in which their biotic communities interact with the physical environment. These may be the differences between better-watered valley floors, valley sides and very dry interfluves. They may also be differences between areas of different rock types.

Energy flows and **nutrient cycling** in arid areas are limited. Herbivores consume between 2 per cent and 10 per cent of the primary production and a large proportion of seeds are consumed by animals such as rodents. Nutrients are normally dissolved from rocks by chemical weathering, then extracted from the soil by plants. However in arid areas, because rainfall is limited, nutrients are stored in the soil and there is little stored in the biomass and litter. After occasional rainstorms, seeds germinate and annual plants grow, extracting nutrients such as nitrogen and phosphorus. The return of nutrients is slow because of slow decomposition. There is little bacterial decay. The dead organic matter may be removed by the wind or occasional surface run-off. Termites and ants (detrivores) consume dead organic matter and this may be more significant than decay by micro-organisms.

Arid and semi-arid ecosystems are considered to be **fragile** because of the limited biodiversity, unreliable rainfall and vulnerability to erosion by wind and water.

The more diverse the ecosystem, the less fragile it may be. For example, a desert grassland with multiple species of grasses and legumes cannot be as easily depleted of its fertility and then eroded as can one with a single kind of pasture grass removing all available nutrients from the ground. In attempting to protect the desert ecosystems, protecting large areas is more effective than having small reserves designed to protect a single species.

The areas are relatively pristine and have seen few changes caused by human activity. The effects of human activity are most clearly seen at the edges of semi-arid areas, in the basins of western North America, along Baja California, and in the drylands of Central Asia and the inland Far East. In North America, Conservation International has estimated that as much as 60 per cent of the entire Sonoran desert surface is no longer covered with native vegetation but is dominated by the 380 species introduced to the region by humans and their livestock. Tamarisk trees choke out native willow and cottonwood seedlings. Invasive weeds such as Johnson grass and Sahara mustard have taken over areas in wildlife sanctuaries and parks in the desert, outcompeting rare native species. Other invasive species such as Africanised bees and cowbirds also compete with the native fauna. As more than 40 dams were constructed along rivers, wetter lands downstream have dried up. Farms and cities pump much more water out of the ground than rainfall in the region can naturally recharge and the water table may fall below the level of plant roots.

Type of plant	Example
Agave	agave parviflora agave murpheyi
Palm	california fan palm (*Washingtonia filifera*)
Cactus	saguaro (*Carnegiea gigantea*) cholla (*Cylindropuntia* spp.) beavertail (*Opuntia basilaris*) hedgehog (*Echinocereus* spp.) fishhook (*Ferocactus wislizeni*) prickly pear (*Opuntia* spp.) nightblooming cereus (*Peniocereus* spp.) organ pipe (*Stenocereus thurberi*)
Legume	velvet mesquite (*Prosopis velutina*) desert ironwood (*Olneya tesota*)
Shrubs	creosote bush (*Larrea tridentata*) bur sage (*Ambrosia dumosa*) indigo bush (*Psorothamnus fremontii*) crucifixion thorn (*Canotia holacantha*) whitethorn acacia (*Acacia constricta*) fairy duster jojoba
Other flowering plants	desert sand verbena (*Abronia villosa*) desert sunflower (*Geraea canescens*) evening primrose ocotillo (*Fouquieria splendens*)
Trees	palo verde (*Parkinsonia florida*) desert willow (*Chilopsis linearis* ssp. *arcuata*) elephant tree boojum tree

Table 10.8 Some examples of plants in the Sonora desert

The differences between the vegetation in hot arid and semi-arid areas

There may be a gradual transition between these areas and there are not two clearly different types. There is also a gradual transition between the semi-arid vegetation and the savannas on the Equator side and the Mediterranean vegetation on the poleward side.

Vegetation of hot arid areas	Vegetation of semi-arid areas
Vegetation is extremely sparse and net primary production may be as low as 3 g/m²/year. However only moving dune belts may be completely without vegetation.	Vegetation is denser and net primary production may be as high as 250 g/m²/year. Some types such as the spinifex (porcupine grass) of northern Australia and the chañaral scrub of central Chile are almost impenetrable.
Plants include tamarisks, clumps of short, spikey grass, dwarf scrub, prostrate plants. Some of the same plants as the semi-arid areas occur but more sparsely and in stunted forms.	The main plant is the deciduous acacia tree. Scrub, thorny succulents and grass also occur.
Most vegetation exists in a dormant state but, after many years without rain, may grow for a few days after a rare rainstorm.	Occasional rainstorms produce short-lived burst of plant growth when shrubs and herbaceous plants blossom.
The number of plant species is more limited.	As in the Sonora Desert (Table 10.8), there may be over 2000 plant species.
Only trophic levels 1–3 may be present (see Fig 10.46).	All four trophic levels are present.
Examples include the central parts of the Sahara, Namib, Atacama and central Australian Deserts.	Examples include the Sonora Desert (state of Sonora, Mexico, southern Arizona, south-east California, most of the Baja California peninsula), coastal Eastern Horn of Africa, Kalahari and Karoo of south-west Africa).

Table 10.9 The differences between the vegetation of hot arid and semi-arid areas

19. Describe the biomass productivity and biodiversity of the arid and semi-arid areas. Refer to trophic levels in your answer.

Adaptation of plants and animals

The plants and animals that live in arid and semi-arid areas have to be adapted to the following features of desert environments.

- Extreme temperatures occur. As discussed earlier in this chapter, some hot deserts have very high diurnal temperature ranges, exceeding 30°C. Daytime temperatures are the highest in the world. Night frosts occur in winter.
- **Drought** is a feature. Different levels of aridity have been discussed earlier in this chapter. The definitions used refer to **physical drought**. This is usually assessed by the balance between precipitation and potential evapotranspiration. The drought may be permanent, as in the centres of the great deserts, seasonal as in the desert margins, or contingent when the expectation of rainfall is high and alternative water supplies have not been developed. **Physiological drought** is when plants suffer from excess concentration of salt in the soil and water is drawn out from the roots by osmosis.
- Soil characteristics are significant. In arid and semi-arid areas there is insufficient rainfall to leach minerals from the soil, this means that the soils are potentially very fertile. The soils form part of the general group known as pedocals where the calcium (which is normally soluble) has not been leached. In semi-arid areas it is possible for potassium and sodium to be leached and the concentration of calcium in the soil is known as calcification. The soils have high pH values. In the more arid areas, only the mobile ions of potassium and sodium enter solution. Intense evaporation at the surface results in the process of **capillary rise** of soil moisture and minerals. This process is **salinisation** and the resulting soils are called **solonchaks**. Plant species vary in how well they tolerate salt-affected soils. Salt tolerances are usually given in terms of the stage of plant growth over a range of electrical conductivity levels. Electrical conductivity is the ability of a solution to transmit an electrical current. Where irrigation water is added to land and allowed to evaporate this can have the effect of increasing salinisation. This process has rendered a lot of land in the Thar desert of Pakistan infertile. Irrigation should always be accompanied by drainage where salinisation is a risk. Many desert soils are grey because they contain salts drawn to the surface in solution after rain and deposited at the surface as the water evaporates.

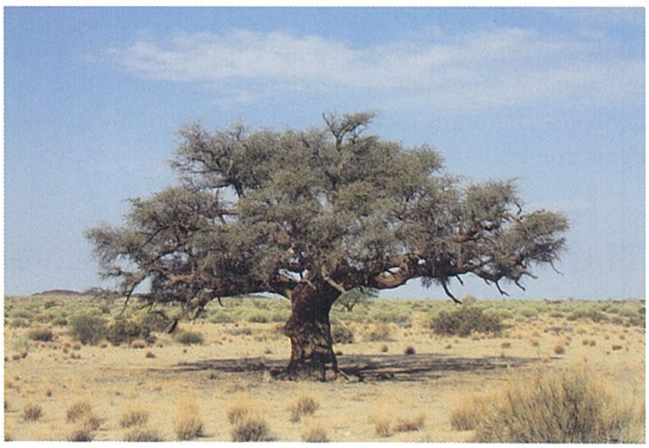

Fig. 10.48 A tree in semi-arid savanna. Notice the relatively small leaf area

Ecosystems in hot arid and semi-arid areas

Most plant adaptations are designed for survival with a minimum amount of water. They include mechanisms to reduce transpiration loss, mechanisms to collect more water and mechanisms to store water and use it effectively.

Mechanisms to reduce transpiration loss

- Many plants have small leaves.
- Many plants have few leaves.
- Plants are deciduous - they lose leaves in the dry season.
- Some plants have no leaves but have spines which also protect them from being eaten by animals.
- Some plants such as cacti have a covering of fine hairs on their stems which provide shade and reduce the desiccating effect of wind.

Mechanisms to collect more water

- Desert vegetation is sparse. The plants are widely spaced because they have to compete for water. Their roots are shallow and wide-spreading to catch water after rain before it evaporates.
- Other plants (e.g. the Joshua tree, a Yucca species, which only grows in the Mojave desert of the USA) have roots up to 10 metres deep (tap roots) to reach down to the water table. This adaptation is most common in low-lying valley floors.

Mechanisms to store water and to use it effectively

- Succulents such as aloes store water after rain in fleshy stems in order to survive through long dry periods.
- Low-growing plants need less moisture for growth.
- Some grass can spring to life after rain, such as the grass in the sands of the Namib desert. The seeds of some desert plants lie dormant for years, then flower and fruit very quickly after rain. They have a very short life cycle.

Fig. 10.49 Cactus growing in a stony desert. Notice the thin soil and the cactus thorns

Fig. 10.50 An aloe flowers in the Namib Desert, Namibia

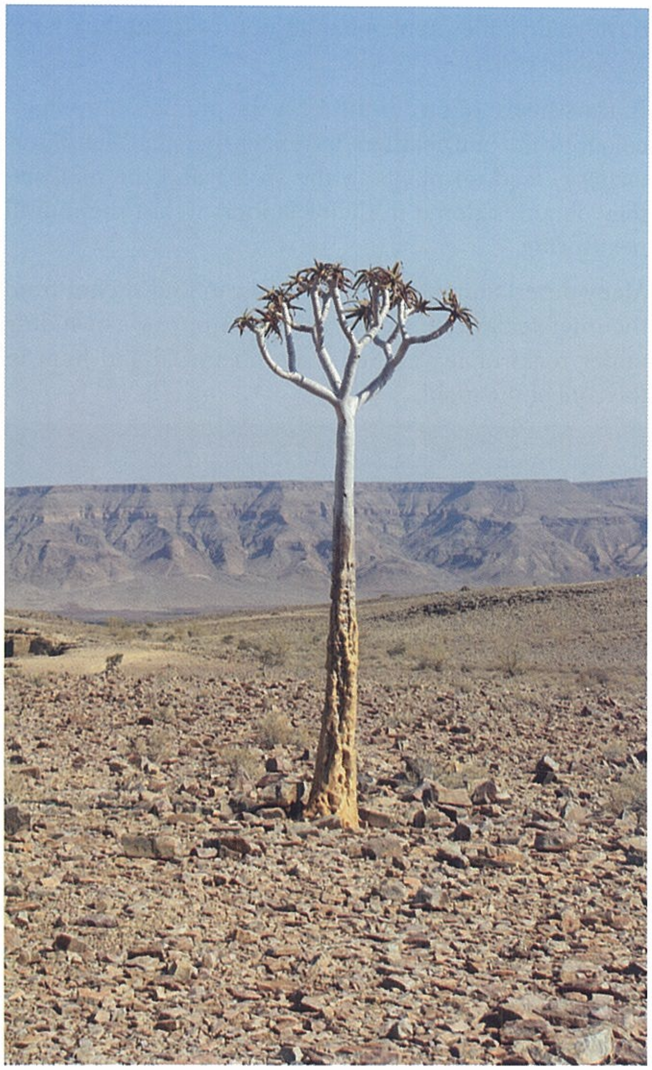

Fig. 10.51 The southern African quiver tree is, in fact, an aloe (*Aloe dichotoma*). The hollow stems were used to carry arrows, hence the name

Adaptations to soil

Soils in deserts are often either rocky or sandy and very porous so water passes quickly into them after rain. Sandy soils are mobile, so plants can easily be covered and they are also loose, so plants can be uprooted. Some plants can survive being uprooted, e.g. tumble weeds. Only salt-tolerant plants, such as saltbush, can grow in saline soils. Desert soils are thin and contain very little organic matter.

Animal adaptation

As mentioned earlier, it is common for the higher trophic levels to be poorly represented or completely absent from the desert fauna. However, there are examples of species that have adapted to survive in very dry conditions. Zebras that migrate in the wet season into the valleys of the Namib desert are able to detect pools of water below the surface with their nostrils. They use their hooves to dig holes to get the water. Some animals, e.g. elephants, travel many miles from one water source to another in the Namib desert.

In the Mojave desert of the USA the animals have light-coloured fur and feathers to reflect the sun. The desert tortoises feed on plants in the spring and the moisture they obtain is stored in their bladders to last them until next spring.

Many desert animals are small and can find shelter from the intense daytime sun by staying in burrows or hiding under rocks or leaves. Some are nocturnal and hunt in the cool of the night.

20. List the key features of arid and semi-arid soils.

21. How are plants adapted to arid and semi-arid soils?

22. How are plants adapted to the arid and semi-arid climate?

The process of desertification and the degradation of soils in semi-arid environments

Many people live in areas where the climate has a dry season and some live in deserts where it is dry all year but they adjust to those conditions and learn to cope with the difficulties of the environment. Contingent droughts occur when rain fails at a time when it is expected to fall and so they cause problems for vegetation and human activities.

Drought can occur almost everywhere but there are areas of the world where droughts are particularly severe and frequent. Drought often goes hand in hand with **desertification**.

Desertification is a term first used by the French scientist Aubréville in 1949. In 1992 the United Nations Environment Program defined desertification as 'land degradation in arid, semi-arid and dry sub-humid areas caused by adverse human impact'. Desertification is not just the spread of deserts and can occur well away from deserts. Today the term is often used to include naturally-induced land degradation. **Land degradation** is the reduction or loss of potential productivity and biological potential by adverse changes in soil characteristics and/or soil loss by water and wind erosion. Natural recovery is not possible or may take so long that, on a human timescale, the changes are considered permanent. As Fig. 10.52 shows, a large part of the Earth's surface is susceptible to desertification. Many of the areas shown, e.g. the Sahel, have:

- a marked dry season
- frequent droughts
- annual potential evapotranspiration which exceeds precipitation
- fragile ecosystems
- soils which lack humus and structure and are therefore loose and easily eroded.

Factors that can trigger desertification include:

- population pressure
- poor land-use practices (over-grazing, over-cultivation, excessive gathering of fuelwood, ploughing up and down slopes, monoculture).

Population growth means a greater need for crops, fuel or animal products. The land is cultivated more intensively, more trees are cut down and more animals are kept. All these factors leave the soil bare and liable to erosion. Once the top soil has gone, nothing can grow and the area becomes a desert.

It is not always easy to distinguish between permanent degradation (the idea of the advancing desert) caused by human activity and the natural variations in the natural vegetation and soil which occur over time due to the sporadic and unpredictable nature of rainfall in arid areas which was discussed earlier in this chapter. The Sahara desert expands and contracts as the rainfall varies from year to year and the vegetation can recover quickly after drought. However, soil can degrade permanently. Water erosion, wind erosion and salinisation are all factors.

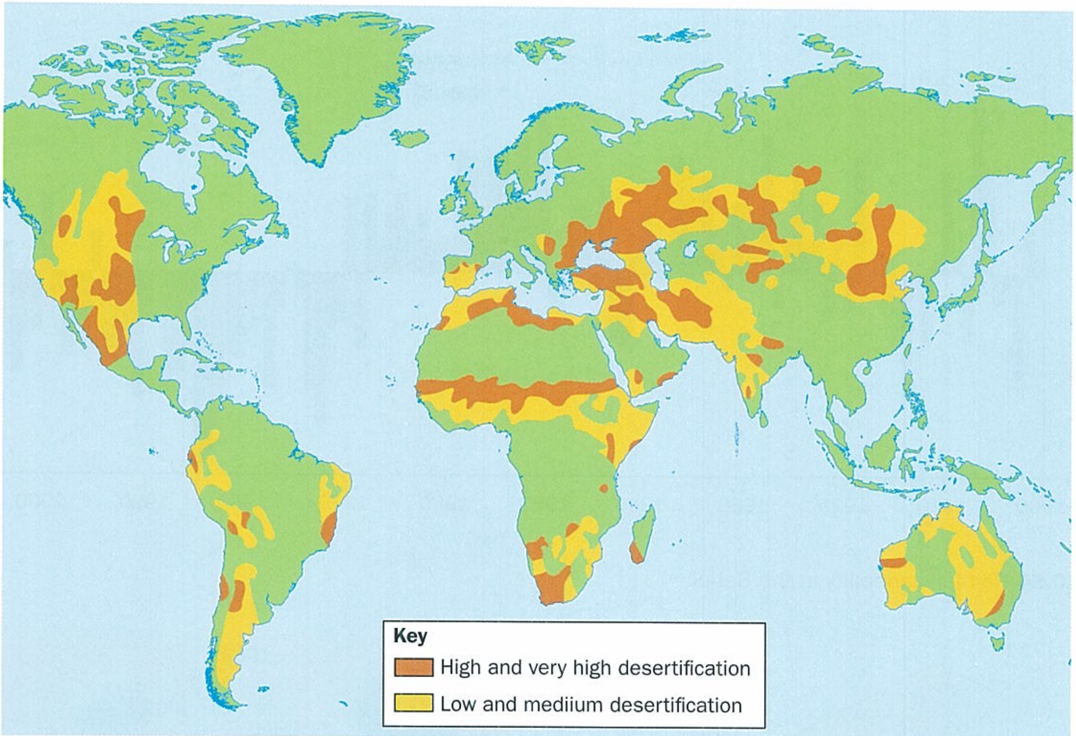

Fig. 10.52 Areas affected by desertification

Sustainable management of arid and semi-arid environments

Case study: The problems of sustainable management in an LIC semi-arid environment and possible solutions: the Sahel

The Sahel is the region which lies between the hyper-arid Sahara to the north and the savanna grasslands to the south. As Fig. 10.3 on page 322 shows, it lies within the region of Köppen's BShs climate of arid, low latitude steppe, with rainfall in summer. Rainfall is unreliable and sporadic and, as Fig. 10.54 shows, a number of wet years is often followed by a run of dry years when the summer rains fail. It is in these years that human activity can lead to desertification.

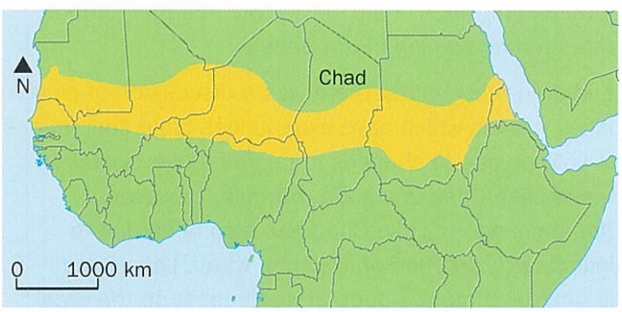

Fig. 10.53 The Sahel

In the dry years, drought reduces the biomass and increases the potential for water and wind erosion of farmland. The Sahara desert was thought to be advancing southwards at a time when drought was extremely severe on its southern fringe, between 1970 and 1993. Then the desert edge retreated north as rainfalls higher than average fell in half the following 12 years. The years since 2000 have mostly been dry.

Chad illustrates many of the complex problems, including desertification, in the Sahel. The northern part of the country is in the Sahara desert and has about 18 millimetres of rainfall a year; however, the southern part is in the Sahel. Mean annual rainfall at Ati is 393 millimetres, nearly all of which falls in the summer months of July and August. High temperatures mean that evaporation losses are high.

The World Food Programme (WFP) describes Chad as a low-income food-deficit country, ranked 184 out of 187 countries on the 2012 UNDP Human Development

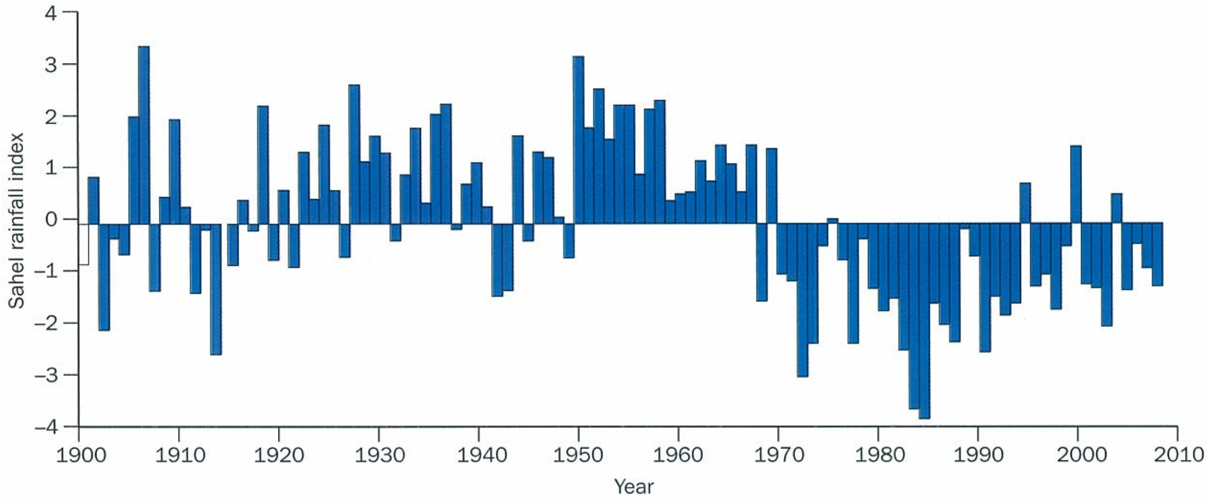

Fig. 10.54 Rainfall variability in the Sahel

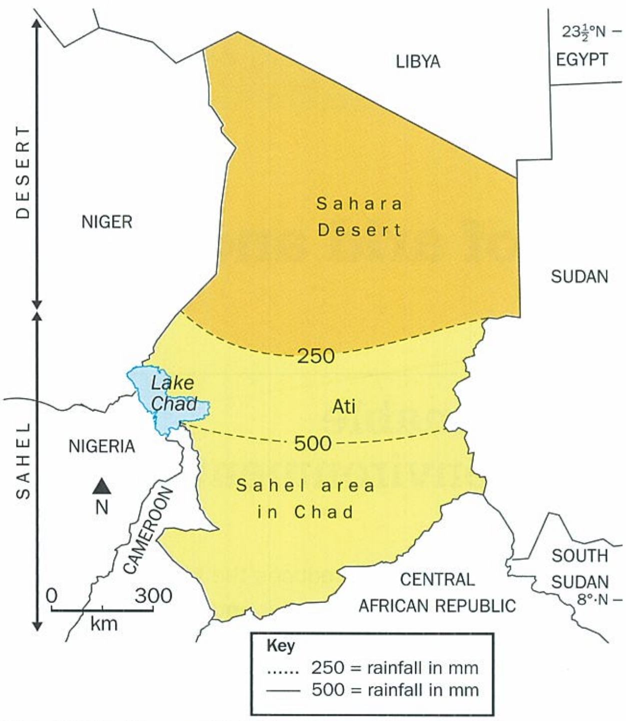

Fig. 10.55 A map of Chad

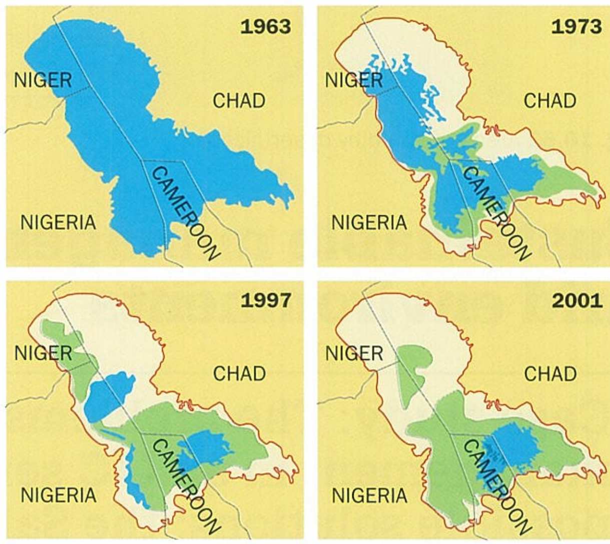

Fig. 10.56 Shrinking Lake Chad. The area in 2013 was similar to that shown for 2001

Index, a composite index of development. Chad has a population of 11.5 million, and 87 per cent of the rural population lives below the poverty line. Poverty in Chad has been aggravated by numerous conflicts during its 50 years of independence. The Sahel of central and eastern Chad is particularly affected by chronic food deficits. Chad has been affected by crises in neighbouring Sudan, South Sudan and the Central African Republic. It is estimated that there are 330 000 refugees in Chad (2013), which puts additional pressure on the limited resources of the already highly vulnerable local population. In addition, there are approximately 700 000 internal refugees because of fighting between government and opposition forces. Chad relies heavily on external assistance for its food security, especially in the Sahel. As well as the erratic rains, cereal production is heavily affected by locust infestations and poor farming practices. The 2011 drought resulted in a 30 per cent deficit in the population's cereal needs. In 2012 there was a severe food and nutrition crisis. In 2013 acute malnutrition rates remained high in the Sahel.

Earlier in this chapter there was a discussion of pluvial lakes – lakes which have experienced large fluctuations in volume due to changes in rainfall and evaporation – and Lake Chad is a good example. However, the shrinkage of Lake Chad has also been due to increased extraction of irrigation water. Lake Chad is only 10.5 metres deep at its deepest so the area fluctuates greatly, although the depth shows seasonal fluctuations only of about 1 metre a year. In 2001 a study published in the *Journal of Geophysical Research* blamed the shrinkage of Lake Chad on over-grazing in the area surrounding the lake, causing desertification and a decline in vegetation. Both the United Nations Environment Programme (UNEP) and the Lake Chad Basin Commission think that at least half of the lake's decrease is due to features of the climate rather than human activity. UNEP thinks inefficient damming and irrigation have caused the rest of the shrinkage.

Lake Chad and the surrounding area has been designated as an ecological catastrophe by the UN Food and Agriculture Organization. Several species are threatened from declining lake levels, notably the endangered painted hunting dog. The birds and animals in the area are threatened as they are important sources of food for the local human population. The only protected area is Lake Chad Game Reserve in Nigeria. The whole lake has been declared a site of international importance under the Ramsar Convention for wetlands.

The water of Lake Chad was shared by Chad, Cameroon, Nigeria and Niger and the shrinking of the lake has resulted in conflicts between the countries that border Lake Chad about the rights to the remaining water. As well as the conflicts that involve the countries, there are conflicts between people living on the lake shores. Farmers and herders want the water for their crops and livestock and are constantly diverting the water. Fishermen however want water in the lake to stay so they can continue to fish.

23. Which rivers flow into and out of Lake Chad?

24. Explain the causes of the shrinkage of Lake Chad.

Less than 3 per cent of Chad is arable land. Population is concentrated in the southern Sahel part of the country where 80 per cent of the population depend on subsistence farming and livestock rearing. The droughts referred to above have resulted in crop failure, destruction of pastures, water supplies drying up and malnutrition.

Population pressure has been a significant factor in desertification. During the wetter than average years shown in Fig. 10.54, rapid population growth occurred and livestock numbers increased. From 1970 onwards, droughts meant that there was no longer sufficient pasture for the animals, so over-grazing occurred and removed the grass; the soil was then exposed and, with no roots to hold it, was easily blown away. Semi-arid soils have little humus and when this was depleted in the dry years, the weak soil structure added to the looseness of the soil. Population growth also resulted in an increased use of fuelwood which left the bare ground prone to wind erosion. Lack of vegetation increased evaporation losses and consequently the water table fell. The increased population used more water from the boreholes for domestic purposes and animals, adding to the lowering of the water table. Population pressure also led to over-cultivation and soil exhaustion.

In the wetter years the soil was unable to recover because the humus and structure had been lost. The increasing frequency of droughts in the Sahel has given communities little time to recover from the last food crisis – savings are exhausted and livestock herds have not been rebuilt. Food prices are abnormally high across the region, further heightening food insecurity.

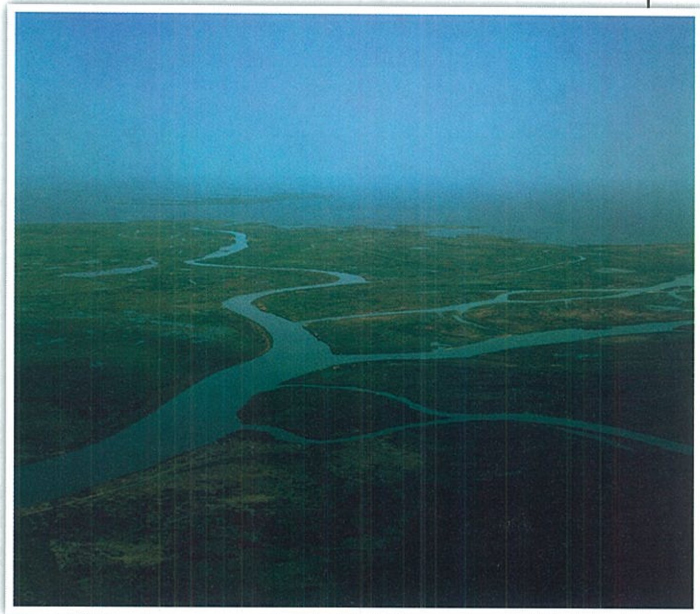

Fig. 10.57 Lake Chad from the air

Fig. 10.58 Fishing on Lake Chad

Aid agencies

The World Population Foundation (WPF) reported that the international response to the 2012 drought in the Sahel region of West Africa averted a humanitarian catastrophe. It was the third drought in less than a decade, so families and communities were already weak. The aid agencies tend to focus on two aspects:

- immediate food assistance, bringing food to millions of people including special foods for young children
- building long-term resilience, e.g. developing methods to limit soil erosion and desertification.

In 2012 US $1.2 billion worth of assistance was provided to 8 million people in the Sahel. In 2013, World Food Programme (WFP) emergency operations formed a plan to support 5.5 million people who were still feeling the effects of the 2012 drought in some way. In 2013 over 9 million people in the Sahel were due to receive WFP food assistance. These included 3.8 million people in Niger, 1.5 million people in Chad, 1.3 million people in Mali, 860 000 people in Senegal, 1.1 million people in Burkina Faso, 510 000 people in Mauritania, 260 000 people in Cameroon and 200 000 people in the Gambia.

In Mali in 2013, a conflict in the north complicated efforts to bring food relief and build resilience. The conflict also forced thousands of families to flee their homes, increasing the numbers of people needing food assistance.

The following is an extract about the World Food Programme in the Sahel in 2013:

WFP is purchasing food stocks and deploying specialised teams to the region for the peak hunger season, which runs from June to September, to ensure that food is available for the most vulnerable – especially women and children. Where markets are functioning, WFP plans to distribute cash transfers and vouchers to 1.6 million people. This helps local economies and gives people a greater variety of food to choose from. In Niger, WFP has supported more than 1.5 million people since its scale up in November, and a new emergency operation focuses on children under two. At the height of the June to September hunger season, WFP plans to reach 2.6 million people with food and cash. Recent assessments in Chad have shown that 3.6 million people are food insecure and malnutrition rates are above the 'serious' threshold in the whole country. WFP's response focuses on nutrition and Food for Work activities. Airlifts have delivered almost 200 metric tons of Plumpy'doz (a food supplement designed to prevent childhood malnutrition) to Eastern Chad. In Mali, WFP is implementing an emergency operation to support 1.3 million people until the end of 2013. WFP is working with local NGOs to provide much needed food assistance in the north of the country where access is limited. A recent assessment in Mauritania showed that 25 per cent of households are food insecure; as 75 per cent of food is imported, food prices strongly affect food security. WFP has launched an emergency operation to reach the most vulnerable through cash transfers, targeted food distributions, nutrition and cereal bank support. As part of its Sahel crisis response, WFP is launching a regional emergency operation to provide food assistance to 555 000 people displaced by the conflict in northern Mali 300 000 internally displaced people in Mali, and 255 000 refugees in Burkina Faso, Niger and Mauritania.

Although droughts in 2005 and 2010 were felt most in Niger and parts of Chad, this year's food crisis is affecting a broad swathe of countries across the Sahel region. Moreover, food prices in the region are much higher than they were in 2010, making access to food even more difficult for vulnerable households. Grain production is below the five-year average in Mauritania (down 46 per cent), Chad (down 37 per cent), Niger (down 23 per cent) and Burkina Faso (down 14 per cent). Many households have not yet recovered from the food crisis of 2010. When households lack coping mechanisms to carry them through hard times, they may resort to selling off their few remaining assets, taking children out of school or migrating to urban areas or neighbouring countries in search of food. Conflict in Mali has resulted in refugee movements and displacement of hundreds of thousands of people, complicating the challenge to provide humanitarian assistance. As a regional drought response, WFP is purchasing food stocks in advance, using its Forward Purchase Facility. This dramatically reduces the time it takes to move food into the remote areas where it is needed most. WFP is committed to purchasing from the region but is looking at all options to ensure that rations can be provided as planned. Malnutrition rates in the Sahel are generally high, especially among young children, and the problem increases in the season before harvest. WFP plans to provide special food assistance to 3.5 million children and pregnant and nursing women most in need. WFP plans to distribute 43 000 metric tons of new nutrition products including Plumpy'sup, Plumpy'doz and Super Cereal Plus. This is nearly twice the amount of specialised nutrition products WFP mobilised for the 2011 Horn of Africa response.

For the latest on WFP's work in Niger go to http://www.wfp.org/countries/niger.

Sustainable farming

This includes measures such as:

- building earth dams to store water in the wet season and then irrigate crops or provide drinking water for animals in the dry season
- planting trees to act as shelter belts to reduce wind erosion and to hold the soil together to prevent water erosion
- encouraging mixed farming so that animal manure provides fertiliser and adds humus to the soil
- reducing stock densities to prevent over-grazing
- contour ploughing and terracing to reduce water erosion
- providing education about crop rotation.

The United Nations Refugee Agency has adopted this approach by planting young trees, including woodland trees such as acacia and fruit trees such as mango. They have also provided the population with firewood to prevent existing trees and shrubs from being cut down. Solar-powered cookers have been introduced.

A sustainable strategy to protect water resources has been developed. It is planned to replace electric pumps with manual ones which are cheaper to maintain. Wells have been dug in dry river beds to preserve the water in the aquifer beneath the water table deep in the rocks.

Large-scale catchment management and inter-basin transfer schemes

So far the only such project completed in Africa is the Lesotho Highlands Water Project which carries water from Lesotho to supply Gauteng in South Africa (not part of a hot arid area). The New Valley Project to transfer water from Lake Nasser on the Nile to the Western desert of Egypt is under construction. Both these are in countries of comparatively high economic development compared to the Sahel. Major schemes needing large capital input have been put forward at various times but so far none have been developed. Plans to divert the Ubangi River into Lake Chad were proposed as early as 1929 by Herman Sörgel in his Atlantropa project and again in the 1960s. The water from the Ubangi would allow Lake Chad to expand and improve incomes from fishing and irrigated agriculture. Interbasin water transfer schemes were proposed in the 1980s and 1990s by Nigerian engineer J. Umolu (ZCN scheme) and Italian firm Bonifica (Transaqua scheme). In 1994, the Lake Chad Basin Commission (LCBC) proposed a similar project, and at a March 2008 summit, the heads of state of the LCBC member countries committed to the diversion project. In April 2008 the LCBC advertised a request for proposals for a World Bank-funded feasibility study.

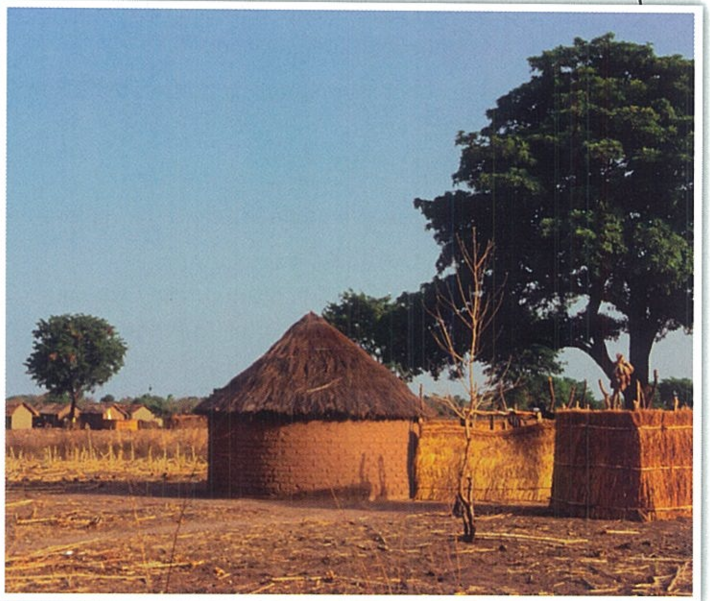

Fig. 10.59 Huts in southern Chad near Kome and Doba

The Great Green Wall (GGW)

This project has been a dream in Africa since the 1980s. The GGW was first proposed in the 1980s by Thomas Sankara, then head of state in Burkina Faso, as a means to stop the growing of the Sahara. The idea was voiced again about 20 years later by the then Nigerian president, Olusegun Obasanjo, who presented it to the African Union (AU) in 2005. The idea was to fight desertification by planting a 'wall of trees' across the continent from Senegal in the west to Djibouti in the east through 11 countries. The original 'wall' was to be 7775 kilometres from west to east and 15 kilometres from north to south. The project has since evolved to become larger and will now involve more than 20 countries. It is to consist of shrubs and herbaceous plants as well as trees and is to be a mosaic rather than a wall. It will skirt around obstacles such as streams, rocky areas and mountains and to link inhabited areas.

The aims of the project are ambitious:

- stopping desertification and erosion
- protecting water sources, e.g. Lake Chad
- restoring and creating habitats for biodiversity
- providing energy resources through fuelwood
- providing fruit, vegetables and other foodstuffs
- supporting local economic development
- promoting political stability – the countries of the Sahel are predominantly Muslim and 2012 and

2013 were years of political turmoil in the Arab world, a neighbour to the GGW countries

- encouraging cooperation, both at the international and communal level
- fighting poverty
- stopping young people migrating from the region.

Financial backing has come from the African Union, European Union, World Bank, UNFAO, Global Environment Facility (GEF) and other international investors. (The GEF unites 182 countries in partnership with international institutions, civil society organisations, and the private sector to address global environmental issues while supporting national sustainable development initiatives. Today the GEF is the largest public funder of projects to improve the global environment.)

Tree planting began in 2011. In Senegal 12 million trees have been planted, particularly indigenous, drought-resistant acacias which will provide local people with a source of income from gum arabic, which is extracted from the bark. It is used as an additive in a variety of food and pharmaceutical products. Trees will also fertilise the soil from their leaf fall and provide shade, reducing evapotranspiration loss. This form of agro-forestry is another example of sustainable farming.

The GGW project has been affected by the various conflicts along the Sahel, particularly those in Mali in 2013 and in Sudan and South Sudan. Opinion is divided as to whether the project will help provide people with a more secure future which will help combat terrorism. Although terrorism has halted the project in some areas, some people believe that it can help political stability in the Sahel.

Criticisms of the project are as follows:

- Some people believe that future world climatic warming may cause the area to become even drier.
- Planting non-indigenous species not well adapted to drought may be an error.
- Ownership of the trees – who looks after them and harvests the crop – is not always clear. The UNFAO believes that consultations with local communities and ensuring their involvement are integral to the project.

Evaluation

Evaluating the success of solutions to environmental problems in the Sahel is not easy. The problems are the result of complex and interrelated factors which are difficult to analyse. The future is also uncertain, both in the physical environment with future climatic changes and the human environment with future population pressure and political conflicts uncertain.

25. List the factors leading to environmental degradation and desertification in semi-arid regions. Divide your list into physical and human factors.

26. Attempt to evaluate the work of aid agencies, local environmental projects and large scale environmental projects in solving environmental problems in semi-arid regions.

Case study: The problems of sustainable management in a HIC hot arid environment and possible solutions: Dubai

Fig 10.60 Skyline of skyscrapers and Burj Khalifa from the desert in Dubai, United Arab Emirates

The city of Dubai is located on the United Arab Emirates northern coastline. Despite being in a hot arid area it has become a global city with a population of over 2 million people. It is a major transport hub through its international airport and the Emirates Airline. Development accelerated when oil revenue started in 1969. Today the economy is based on tourism, aviation, real estate, manufacturing and financial services. It is noted for its high-rise buildings such as the world's tallest building, the Burj Khalifa.

Environmental issues associated with rapid expansion of a city in a hot arid area have included:

- Waste and sewage disposal. At times raw sewage has been released into the Persian Gulf. Waste water is transported to the treatment plants by 4000 trucks. Water treatment has struggled to keep up with increased demand but in 2010 a large treatment facility was opened, doubling capacity.
- Water supply, which involves desalination of sea water resulting in raising salinity levels in the sea. The Persian Gulf's salinity levels have risen to 47 000 parts per million, from 32 000 about before the rapid growth of the city, threatening marine life. The emirates desalinate the equivalent of four billion bottles of water a day. At any given time, the region has, on average, an estimated fresh water supply of just 4 days. Desalination plants release carbon dioxide and result in a large carbon footprint.
- Energy issues – desalination, running the air-conditioned city, major industrial projects like aluminum smelting and steel production require much electricity.

Measure to develop sustainability include:

- setting up a groundwater monitoring system to check levels of the water table and salinity
- increasing recycling
- irrigating lawns with residual waste
- develop water storage facilities to give longer back-up supplies
- requiring new buildings to be designed using environmental standards that set goals for water and energy consumption
- importing natural gas from Qatar
- developing solar energy and wind power, although these are still in their infancy
- developing nuclear power: the United Arab Emirates have agreed to build nuclear plants that do not enrich or reprocess uranium. Abu Dhabi plans to build four plants by 2017 and to generate about 23 per cent of the Emirates' power by 2020.

Key concepts

The key concepts listed in the syllabus are set out below. For each one a summary of how it applies to this chapter is included.

Space: hot, arid and semi-arid environments cover a significant proportion of the Earth's surface space and occupy particular spaces on the globe. The hot arid spaces lie in the 'horse latitudes', the areas of the subtropical high pressure systems roughly 30–35° north and south of the Equator. These are spaces with descending air, gentle pressure gradients and calms. Easterly Trade Winds blow out of the regions towards the Equator and westerly winds blow out towards the poles, resulting in an offshore movement of air.

Scale: time scale is important to the desert environment. Some desert processes like weathering are extremely slow whereas features such as flash floods are high magnitude, low frequency events. The pattern of landforms is made more complex because many desert landforms are likely to have formed in past climates, even going back to the Tertiary Period. Desertification illustrates the rapid change happening today in some semi-arid areas. The differing spatial scale is illustrated by the huge global scale of areas such as the Sahara, the regional scale of particular landscapes such as dune fields and the microscopic scale of processes such as salt weathering.

Place: distinctive arid landforms are found in places with similar geology. For example, a place that has horizontal strata and has been relatively stable is more likely to have a landscape of plains, escarpments and mesas. The vegetation is similarly distinctive, although individual species may be restricted to particular places, as illustrated by the native plant species of the Sonoran Desert, described in this chapter. Human activity may depend on other features of the place such as oil or mineral deposits, level of development or tourism.

Environment: arid and semi-arid environments are the most challenging for human activity. Areas such as the Sahel support agricultural populations in LICs and lower MICs, where people are at the mercy of drought, soil erosion and crop failure due to the sporadic nature of desert rainfall. In contrast the development of cities such as Las Vegas and Dubai in HICs shows that human activity can dominate the environment. However the growth of these cities raises issues of environmental sustainability, particularly related to water and energy supplies. Environmental management is a key issue in arid and semi-arid areas.

Interdependence: arid and semi-arid ecosystems are considered to be fragile because of the limited biodiversity, unreliable rainfall and vulnerability to erosion by wind and water. This means that the interdependence of humans and the environment is particularly sensitive. The process of desertification described in this chapter shows how interactions between people and their environment create the need for environmental management and sustainability and complex interacting physical and human systems.

Diversity: arid and semi-arid landscapes are diverse and subdivided into ergs, reg and serir. There is further diversity because some landscapes are the result of wind action and others the result of water action. The effect of climatic change of landforms introduces further diversity. Arid and semi-arid areas may have a large ecosystem diversity. There may be the differences between better-watered valley floors, valley sides and very dry interfluves. There may also be differences between areas of different rock types. Flora and fauna in arid and semi-arid areas are relatively species-poor, in other words less diverse than other biozones.

Change: there is overwhelming evidence that today's deserts have been affected by climatic change and that past climates have had an important role in the development of landforms. These changes and their effects are described in this chapter. Today population pressure can cause dramatic changes in semi-arid environments, such as desertification, illustrating the dynamic nature of these areas. Where mineral resources and oil are extracted, or where cities such as Dubai are developed, change is significant.

Exam-style questions

1 Study Fig. 10.61 which shows a desert landscape.

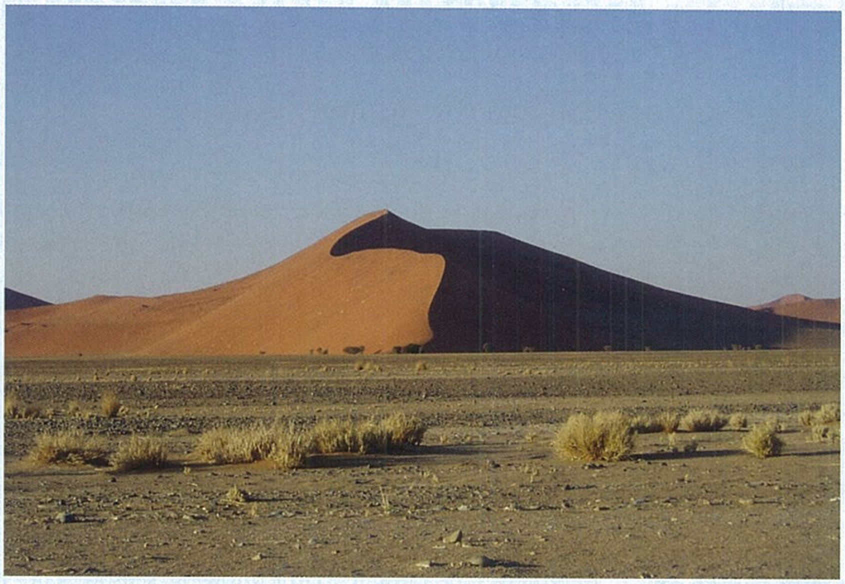

Fig. 10.61 A desert landscape in Namibia

(a) Describe the landforms and vegetation shown in the photograph. [4]

(b) Explain the role of weathering and erosion in the formation of the landforms. [6]

2 Describe the evidence for climatic change in deserts and explain how past climates have influenced landform development. [20]