9 Hazardous environments

In this chapter you will learn about:

- Hazards resulting from living in areas which have tectonic activity, unstable slopes and **atmospheric disturbances**.
- Primary and secondary effects of hazard events on lives and property.
- The extent to which hazards can be predicted and methods used to monitor them.
- Difficulties involved in managing environmental hazards sustainably and examples where management has achieved some success.

Terms used in hazard studies

- **Hazard** – a threat that could injure people and damage the built environment. An earthquake in an unpopulated area is a physical event; it only becomes a hazard when people put themselves in danger by moving into the area. Natural hazards occur only where humans interact with the physical world and their severity and frequency depends on human activity.
- **Disaster** – a hazard that causes so much damage and injury that recovery without help is impossible.
- **Risk** – the exposure of people to a hazard event.
- **Vulnerability** – the degree to which conditions make a population more likely to experience a hazard event, which they do not expect, cope with or recover from.
- **Resilience** – how well a population recovers from a disaster.

Classification of hazards

- Cause:
  - tectonic (geological) – earthquakes and volcanic eruptions
  - geomorphological (processes acting on the land surface) – mass movements
  - atmospheric (meteorological) – tropical cyclones and tornadoes
- Magnitude, scale or size; some types have their own scales
- Frequency of occurrence
- Length of warning time – rapid onset hazards are much more dangerous than slow onset ones
- Spatial distribution.

RESEARCH Choose one recent hazardous event and make notes on it. Include date, (local) time, location and size of the event and to what extent these factors influenced the hazardous event's impacts on lives and property. Also note its causes, the methods of and extent to which it was predicted, monitored and its risks perceived. Note its primary and secondary impacts on lives and people and whether they were local, national or global in scale.

Hazards resulting from tectonic processes

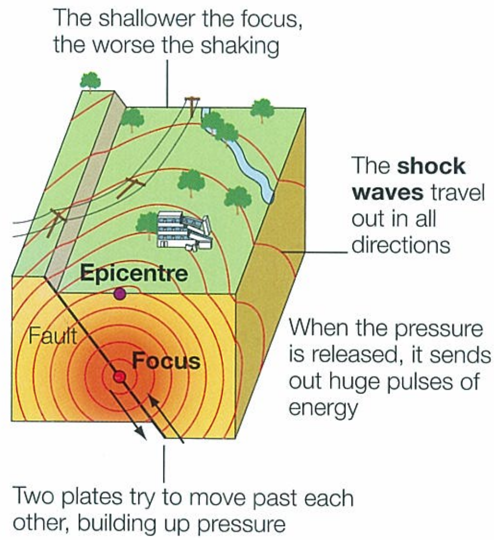


Fig. 9.1 Three-dimensional block diagram showing how earthquakes occur

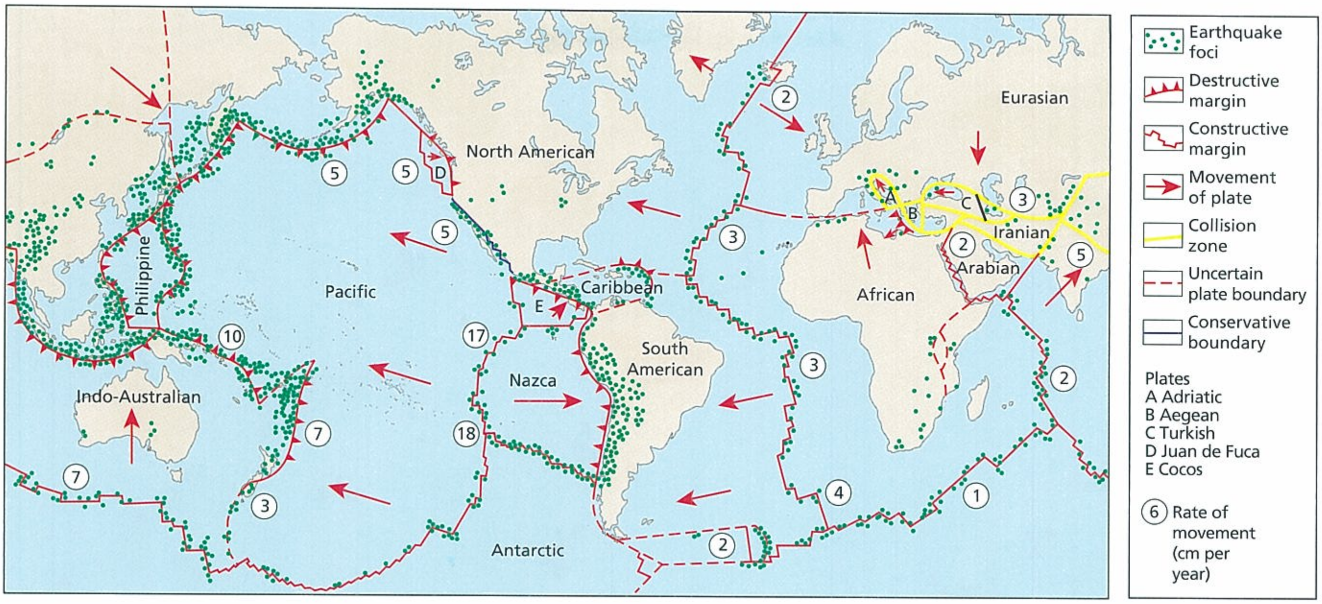


Fig. 9.2 The global distribution of earthquakes

The global distribution of earthquakes and volcanoes related to plate tectonics

Earthquakes

Most earthquakes are tectonic; they occur on all types of plate boundary, at hot spots away from plate boundaries and at **fault** lines. When two plates try to move but become stuck against each other, stress builds up. Eventually, the plates break free along a fault, causing a sudden release of pressure and releasing a tremendous amount of energy, which sends **seismic waves** (shock waves) out from the point of movement - the **focus** or origin of the earthquake. The point on the Earth's surface immediately above the focus is the **epicentre**. Seismic waves are strongest at the epicentre but the greatest damage does not always occur there.

Most earthquake foci occur in narrow zones along plate boundaries but their effects extend far beyond the plate boundary. There are four types of seismic zone:

- **Destructive** (convergent) plate margins have shallow, intermediate and deep earthquakes inclined along the Benioff zone on the subducting plate where slab pull occurs.
- Collision boundaries of two converging continental plates, such as between the Eurasian and Indian plates where the Himalayas formed.
- **Conservative** plate margins where faults, such as the San Andreas in California, have earthquakes but no volcanic activity. Here the North American and Pacific plates are moving side-by-side. Great friction builds up between the plates as they catch against each other which is eventually released in very powerful earthquakes, usually from a shallow focus.
- Constructive plate margins at mid-ocean ridges where ridge push (slab push) occurs. The lithosphere is too weak and thin for a lot of stress to build up, so large earthquakes do not occur. They are usually shallow focus and occur with volcanic activity.

Some powerful earthquakes may be non-tectonic, caused by human activity putting too much stress on faults. The 7.9 magnitude earthquake in Sichuan, China, in 2008, which killed nearly 70 000 people, was linked to the construction of a reservoir, which added a very heavy weight of water to the surface.

Volcanoes

A volcano results from the build-up of molten material emitted onto the surface through an opening or fissure in the crust.

> **1.** Describe the distribution of active volcanoes in relation to the plate boundaries on Fig. 9.3. Note that the plate boundary to the north of India where two continental plates meet does not have active volcanoes. Note where active volcanoes are found away from plate boundaries.

An **active volcano** has erupted in the last 80 years (some define it as a volcano that has erupted in historic time). **Dormant volcanoes** are inactive but may become active again in the future, whereas **extinct volcanoes** will not erupt again.

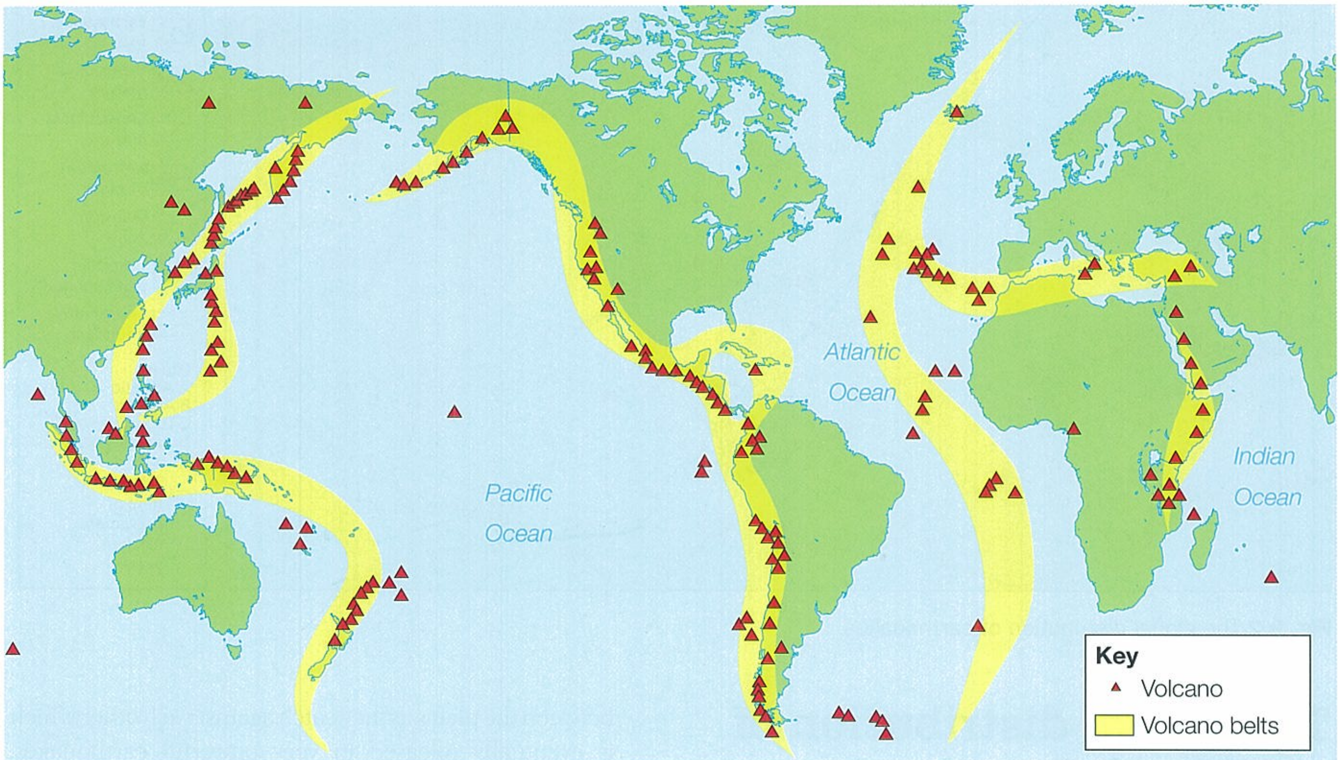


Fig. 9.3 The global distribution of active volcanoes

Earthquakes and resultant hazards

Shaking

Earthquakes send out seismic energy waves, which are recorded by seismographs. **Primary (P) waves** travel fastest and arrive at a place first, followed by **secondary (S) waves**. The slowest waves, **surface waves**, travel along the Earth's surface. Being long waves with large amplitude, they cause most of the damage as they shake the ground most violently.

Measuring earthquakes

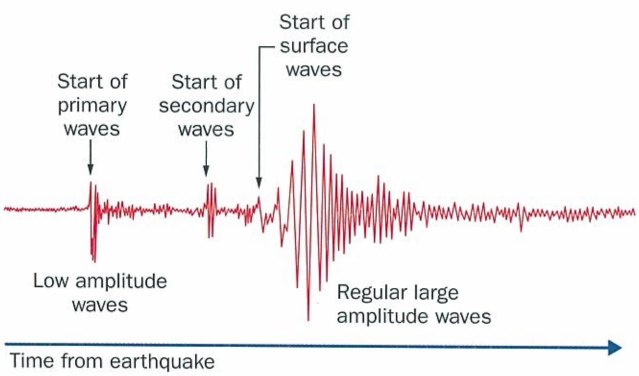


Fig. 9.4 A seismograph recording of an earthquake

The total amount of energy released, or **magnitude** of an earthquake, was measured on the **Richter scale**. Since 1993, the USGS used the more sophisticated Moment magnitude scale which is similar for medium earthquake values up to 5.0. Both are log scales, so an increase of 1, e.g. from 4.5 to 5.5, produces ten times more ground movement and releases 32 times more energy.

The number of earthquakes increases as their magnitude decreases.

The 12-point **Mercalli scale** measures the **intensity** (amount of physical damage) of an earthquake. Isoseismal

Magnitude (Moment magnitude scale)	Descriptive term	Average number per year over a recent 50 year period	Effect in populated areas
8 and above	Great	1	Very large-scale devastation with a high death toll.
7–7.9	Major	18	Lots of structural damage and many deaths.
6–6.9	Strong	266	Considerable structural damage and some deaths.
5–5.9	Moderate	1319	Some structural damage but deaths are rare.

Table 9.1 Earthquake frequency by magnitude

Value	Intensity	Description
1	Instrumental	Not normally felt. Animals uneasy.
2	Feeble	Felt only by a few people at rest
3	Slight	Vibrations like a lorry passing. Felt by people at rest.
4	Moderate	Felt indoors by many. Cars rock.
5	Rather strong	Sleepers awakened. Some windows broken.
6	Strong	Bells ring. Trees sway. Loose objects fall.
7	Very strong	Difficult to stand up. People run outdoors. Walls crack.
8	Ruinous	Ground cracks. Pipes break.
10	Disastrous	Landslides. Many buildings destroyed.
11	Very disastrous	Few buildings left standing.
12	Catastrophic	Total damage. Ground surface rises and falls in waves. Objects thrown into the air.

Table 9.2 The Mercalli scale of earthquake intensity

lines on a map can be drawn using Mercalli scale measurements.

The focus (origin) of an earthquake can be up to 700 km deep. Below that the rocks are so hot they bend, rather than break. Deep focus earthquakes are generally not as destructive as shallow focus ones because the thickness of rocks above the focus absorbs the shockwave. Its strength reduces with increased distance from the focus.

Buildings can be destroyed both by shaking and by the ground tilting or subsiding as the shock wave passes.

Secondary earthquake hazards

Secondary hazards result from the shaking of the ground.

- → **Landslides**: in April 2015 a shallow, 7.9-magnitude earthquake struck Nepal with its epicentre 80 km north-west of Kathmandu. Climbers at south base camp on Mount Everest, about 200 km away, reported that after the ground shook there was a massive fall of rocks, snow and ice down the mountain, causing 19 deaths in the camp. Frost-shattered rocks had broken free when shaken and gravity moved them quickly down the steep slopes. Landslides blocked roads, delaying the arrival of aid.
- → **Soil liquefaction** occurs when the shaking of the ground makes weak or unconsolidated rocks act as a liquid and flow, leading to the sinking and destruction of buildings. This occurs when groundwater is near the surface and soft sediment like sand mixes with water.
- → **Tsunamis** are high, long-period waves in the ocean, resulting from a sudden displacement of the sea bed along a fault. In the open ocean tsunami wave crests are small and wave lengths very long, making them difficult to monitor. When the wave crests reach shallow water at the coast, they slow and rise dramatically in height. The waves then retreat, pulling water back out to sea, before returning to hit the coast with tremendous force. Their height can exceed 30 m and they can flood coasts thousands of kilometres away from the focus.

Coastal areas near earthquake epicentres have little or no warning because a tsunami travels very rapidly. The tsunami generated by the large earthquake off the west coast of Sumatra on 26 December 2004 reached Aceh province a few minutes afterwards, so people fleeing from the earthquake were caught in the flood that surged inland.

Floods

More damage, injury and death occurs if a shock wave causes a dam wall to collapse or a large landslide to fall into a lake, resulting in sudden flooding down valley.

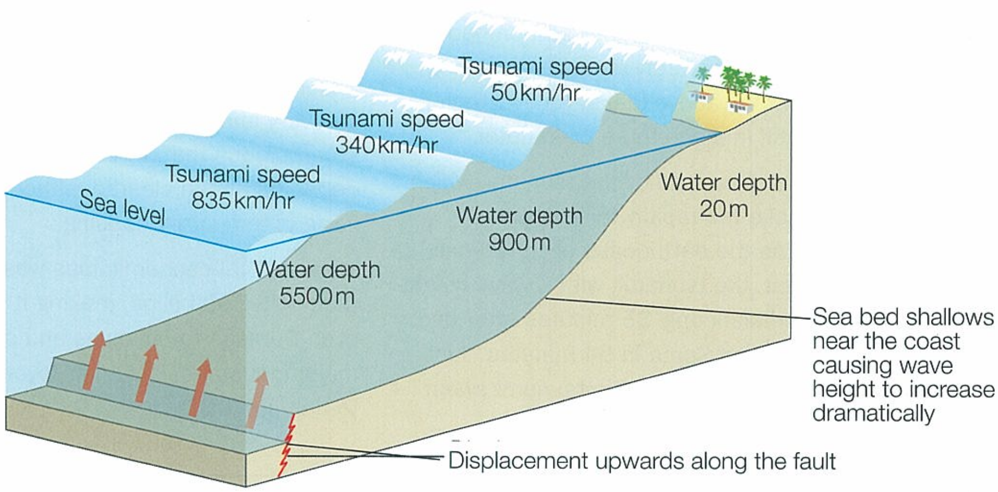


Fig. 9.5 Three-dimensional block diagram showing how a tsunami forms

Case study: The Tohoku (Sendai) earthquake and tsunami in Japan, 2011

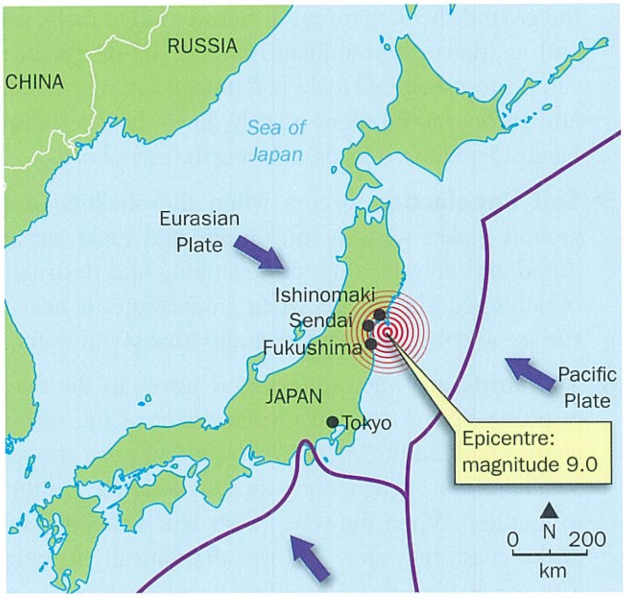


Fig. 9.6 The location of the epicentre of the Tohoku (Sendai) earthquake

The magnitude 9.0 earthquake occurred at a depth of 32 km off the north-east coast of Honshu, Japan's main island, where the Pacific plate begins to subduct beneath the Eurasian plate at a rate of 83 mm a year. Thrust-faulting uplifted the sea floor by 35 m. The tsunami affected at least 2000 km length of densely populated coastal lowlands. Nowhere in the world was better prepared for earthquakes but the sea defences proved to be totally inadequate, as no one imagined waves as high as 10 m would occur. In fact, a wave nearly 38 m high hit the settlement of Miyagi.

Effects on lives and property

The earthquake caused fires in all the affected cities and in an oil refinery. Millions of homes were without power, as the Fukushima nuclear power station had to be closed down. It was severely damaged, causing partial meltdown and radioactive leaks. An evacuation zone around it was still in place three years later.

Most of the deaths were caused by the tsunami, which followed the earthquake too rapidly for adequate warning to be given. As the earthquake occurred only 129 km from the coast, the tsunami, with a wave height of 4.1 metres, hit Kamaishi only 35 minutes after and a 7.3 m high wave reached Soma in 64 minutes. Just over an hour after the earthquake, the tsunami swept planes away at Sendai airport.

The configuration of the coast amplified the tsunami, as it funnelled into bays and up estuaries. Rikuzentakata, a settlement with a population of over 23 000, was totally submerged by a wave as high as the third floor of the city hall. Few buildings were left standing in any of the affected cities. The wall of water swept buildings, ocean-going ships, trains and vehicles kilometres inland and piled them up.

In total, the tsunami inundated 561 km^2 and destroyed 100 tsunami evacuation sites. The total death toll was 20 896, with more than 5000 injured and 130 000 homeless. Approximately 332 000 buildings, 2000 roads, 55 bridges and 26 railways were destroyed or damaged. A dam collapse near Fukushima destroyed 1800 homes. Most casualties and damage occurred in the cities of Iwate, Miyagi and Fukushima.

Fig. 9.7 The town of Ishinomaki four days after the tsunami struck

Severe damage to the infrastructure made rescue and recovery immensely difficult but the relief mission was so enormous that, three years afterwards, most of the debris had been cleared, although people were still living in temporary housing.

Japan's total economic loss was estimated to be more than $US 300 billion, making it the costliest disaster ever. Damage to buildings and supply lines caused major industries, including Toyota, Honda and Nissan, to halt production.

Location	Month/ year	Mg*	Depth of focus (km)	Deaths	Circumstances
Indian Ocean off the west coast of north Sumatra (3.30 N, 96 E)	December 2004	9.1	30	227 898 (mainly by tsunami)	Release of stress on the subducting Indian plate by a 20 m vertical displacement and a 300 km horizontal rupture along a thrust fault at the boundary with the Eurasian plate, 250 km from the coast.
Tohoku (Sendai) off the east coast of Honshu, Japan (38.30 N, 142.37 E)	March 2012	9.0	32	20 896 (mainly by tsunami)	Rock moved 35 m up and a 300 km rupture occurred along a thrust fault at the destructive plate boundary, 129 km from the coast.
Off the coast of central Chile (35.85 S, 72.72 W)	February 2010	8.8	35	547	Horizontal movement along a fault on the subducting Nazca plate, 95 km from the coast.
Off the west coast of north Sumatra (2.3 N, 93 E)	April 2012	8.6	23	10 (8 from heart attacks)	Horizontal movement along a fault 434 km from the coast of Sumatra and 200 km from the subduction zone.
Off the coast of southern Sumatra (4.44 N, 101.39 E)	September 2007	8.5	34	25	Movement along a thrust fault on the boundary of the Australian and Indian plates, 130 km from the coast.

Mg* = Magnitude

Table 9.3 The strongest earthquakes since 2000

Location	Date	Mg**	Focus depth (km)	Deaths	Effects on lives and property
Haiti (18.44 N, 72.57 W)	January 2010	7.0	13	About 200 000*	1.5 million people (estimated) homeless in the densely-populated capital city. Damage to airport, port and roads slowed the arrival of aid.
Indian Ocean off the west coast of north Sumatra (3.30 N, 96 E)	December 2004	9.1	30	227 898 (mainly by tsunami)	The most deaths ever recorded in a tsunami. Deaths in 14 countries in densely-populated coastal lowlands in south east Asia and one in east Africa. Aceh (Indonesia) was the most affected area.
Sichuan, China (103 N, 33 E)	May 2008	7.9	19	87 587	No aid for days as landslides blocked and destroyed roads. Landslides also buried a train and killed 700 in a settlement.
Kashmir, Pakistan (34.53 N, 73.58 E)	October 2005	7.6	26	86 000	No aid for days as landslides blocked and destroyed mountain roads. Many children died when poorly-built schools collapsed.
Bam, south-east Iran (29 N, 58.31 E)	December 2003	6.6	10	31 000	Landslides in the area around the epicentre trapped people in their poorly-built, mud brick homes when heavy concrete roofs and ceilings collapsed. Houses lacked building regulations.
Tohoku (Sendai) off the east coast of Honshu, Japan (38.30 N, 142.37 E)	March 2011	9.0	32	20 896 (mainly by tsunami)	Tsunami – at its maximum nearly 38 m high – caused most of the deaths. Economic loss 300 billion $US.

* The real total is unlikely to be known. Estimates vary from 316 000 (Haiti government) to 85 000.

****Mg** = magnitude (Moment magnitude scale).

Table 9.4 Earthquakes causing the most deaths since 2000

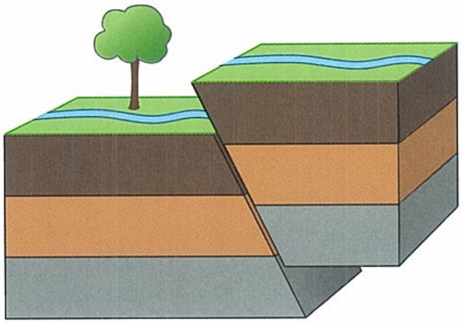


Fig. 9.8 A thrust fault

Outbreaks of disease occur when survivors are forced to live in camps with insanitary conditions.

Is there a relationship between earthquake magnitude and deaths?

Although the magnitude in the above data tables can be plotted on a linear scale, the great range of deaths makes it impossible to plot them on a normal linear scale scattergraph. **Semi-logarithmic graph** paper (**log-normal graph** paper), with one linear scale and the other logarithmic, must be used. On Fig. 9.9 the log scale has cycles, each of which is given a value ten times the size of the adjacent lower cycle. The start of the cycles can be 0.1, 1, 10, 100, 1000, 10 000, and so on. As with all scattergraphs, the scales do not need to extend to values below the lowest values in the data. This graph starts at 100 because there are not enough cycles on this paper to show values below 100. The first cycle is subdivided 100, 200, 300, etc.

2. (a) Comment on what Fig. 9.9 shows about whether or not there is a relationship between earthquake magnitude and deaths.

(b) Plot another semi-log scattergraph of the same earthquakes to show earthquake deaths and depth of focus. Comment on a conclusion that can be made from your graph.

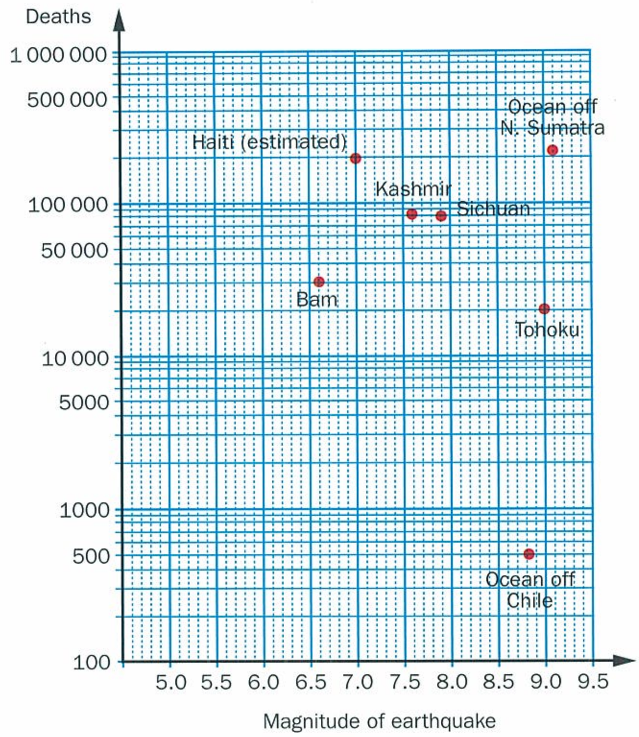


Fig. 9.9 Semi-log graph showing earthquake magnitude and deaths

3. (a) Use htpp://usgs.gov/earthquakes to search in the significant earthquake archives for eathquakes with a magnitude of 8.0 or higher that have occurred since 01-01-2000. Choose the map and list format. Print a list of them.

(b) Use the map of the earthquakes to comment on the areas of greatest activity since 2000 and to what extent it is possible to predict where the next very strong earthquake will occur.

4. Using evidence from Tables 9.3 and 9.4, explain why two of the strongest earthquakes also resulted in many deaths. To what extent were their death tolls caused by the shock waves passing through?

RESEARCH The USGS website (htpp://earthquake.usgs.gov/earthquakes) has a wealth of information. Look up the Real-time earthquake maps to find information about earthquakes that occurred in the last day, week or month and which plate boundaries are most active. Note any earthquakes with a magnitude 8.0 or higher that have occurred since 2013.

Case study: A comparison of the Haiti and Christchurch earthquakes

Earthquake location	Date and local time	Magnitude	Depth of focus	Deaths
Port-au-Prince, Haiti	January 2012 16.53	7.0	13 km	200 000 (estimated)
Christchurch, New Zealand	September 2010 04.35	7.1	5 km	0
Christchurch, New Zealand	February 2011 12.51	6.3	5 km	185

Table 9.5 The Haiti and Christchurch earthquakes

It is clear that the enormous difference in deaths cannot be explained by magnitude, time of day or focal depth. Also, the epicentre of the Haiti earthquake was 25 km from the city whereas that of the 2011 Christchurch earthquake was only 10 km from the city centre. However, Port-au-Prince had a population of 2.5 million, whereas only 400 000 lived in Christchurch.

The Haiti earthquake

Devastation resulted from a tiny fragment of the Caribbean plate moving eastwards along a fault on the destructive plate boundary with the North American plate. The shallow depth of the movement caused much damage from shaking, which lasted for nearly a minute.

Effects on lives and property

- The Haiti government's estimate of 316 000 deaths is believed to be too high: other estimates suggest 200 000. As people were buried quickly in mass graves to reduce the incidence of disease, it was difficult to keep proper records. More than 100 000 are estimated to have been injured and up to 1.5 million left homeless.

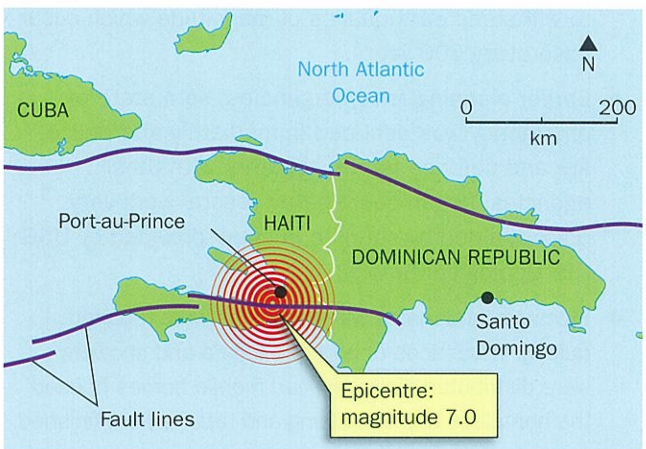


Fig. 9.10 The Haiti earthquake, January 2010

- Hospitals and government buildings were destroyed, as well as 250 000 residences and 30 000 commercial buildings.
- Power and water supplies were disrupted and phone communications lost.
- Incoming aid was delayed because the international airport's control tower and the port were destroyed and many roads were blocked.
- Looting and violence was a problem for relief workers trying to keep stocks of food and water safe and to distribute them.
- More than 3000 died in 2010 in cholera outbreaks caused by poor sanitation in the temporary tented camps. Outbreaks continued and, by 2015, cholera had killed about 8600 people.

Reasons for the severity of the earthquake

- It struck the densely-populated capital city.
- Liquefaction: much of the city was built on loose sediments, which allowed the seismic waves to amplify.
- The international airport had only one runway, limiting the number of planes carrying aid and aid workers that could land.
- Haiti is a very poor country and without building regulations, so most infrastructure had been constructed cheaply. Buildings were not reinforced and many had no foundations. Heavy concrete buildings collapsed because they had little steel in their support columns.
- Many people lived in shacks made of flimsy materials on very steep, unstable slopes.
- The earthquake was unexpected and the country unprepared because the last damage from an earthquake was in 1770.

- Haiti had no army and few emergency service vehicles or staff to give immediate assistance.

It is clear that the perception of risk from an earthquake was minimal, but the government acted on the cholera risk by relocating many people to areas with better sanitation.

Recovery

Haiti had poor resilience as recovery depended largely on overseas aid. Three years after the earthquake, just over half the debris had been cleared and about 280 000 people were still living in camps, some of which lacked flushing toilets. One-fifth of the population lost their jobs because clothing factories, the largest employer, had been destroyed.

Despite the extensive scale of the devastation, the economic cost of the earthquake is believed to be relatively small, less than $US9 billion. Few people were insured against losses, so the biggest cost was for rebuilding.

The Christchurch earthquakes

Almost all the damage was done by the 2011 aftershock earthquake, partly because the higher magnitude 2010 earthquake had already weakened and damaged structures, so less shake was needed to cause collapse. Some parts of the city had been damaged by liquefaction. Also the 2011 earthquake focus was shallower, closer to the city centre and at Tuesday lunchtime when many people would be out, rather than in bed on a Saturday morning, as in the 2010 event.

Both earthquakes resulted from deformation along different thrust faults at the destructive plate boundary where the Pacific plate subducts beneath the Australian plate.

Effects on lives and property of the 2011 earthquake

- Vertical and horizontal shaking at the same time destroyed 1000 major buildings. The shaking intensity was more than four times that in Haiti, and one of the highest ever recorded.
- Liquefaction undermined the foundations of many buildings and destroyed houses built on soft sand by the river in the eastern suburbs. The tallest hotel, the Grand Chancellor, dropped on one side by one metre.
- Numerous aftershocks made recovery difficult.
- More than half the 185 deaths occurred inside the TV building, which collapsed and caught fire. At least 1500 people were injured.

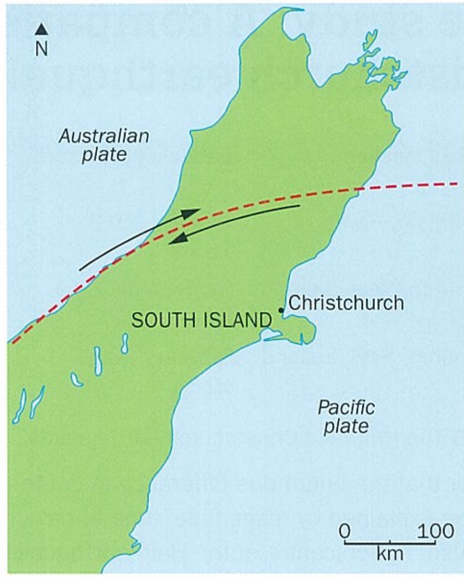


Fig. 9.11 The location of Christchurch in relation to the plate boundary

- Most water and sewerage systems were damaged and power cuts affected many homes. However, many services were restored within a week and most within a fortnight. Phone communications were only disrupted for a short time.
- Liquefaction forced road surfaces upwards, slowing rescue efforts.
- The total economic cost of the earthquake is about $US 40 billion, mostly for rebuilding and insurance losses.
- The international airport was undamaged, so overseas aid arrived quickly.

Perception of the risk

Action by government agencies gave high resilience and considerably less severe effects than in the Haiti earthquake:

- Strict building codes, so modern buildings were built to withstand earthquakes of magnitude which occur once every 500 years.
- Earlier planning for emergencies, so a state of emergency was declared immediately and police, fire and defence forces, together with other agencies, began coordinated rescue work very quickly, aided by satellite imagery provided by USGS (US Geological Survey).
- Electricity and mains water supplies were repaired quickly. Thousands of portable toilets and showers were distributed. Fully-serviced mobile homes housed the homeless until rebuilding and repairs were finished.

All new buildings were made earthquake-proof with a maximum height of 28 metres.

5. List the reasons why damage and deaths in earthquakes of the same magnitude in cities in LICs are greater than in cities in HICs.

Volcanoes and resultant hazards

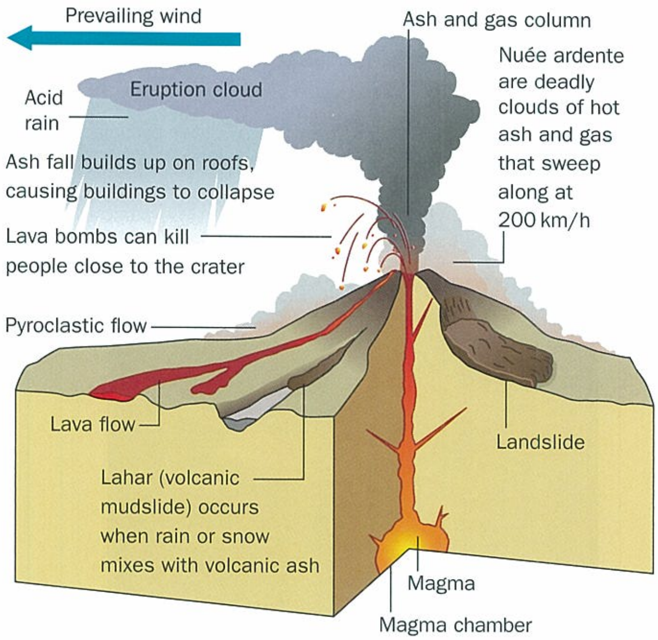


Fig. 9.12 Three-dimensional block diagram showing primary volcanic hazards that result directly from volcanic eruption

Volcanic emissions – primary hazards

Gases

Water vapour constitutes up to 80 per cent of the gases emitted and, after conversion to rain, is responsible for dangerous mudflows and lahars. Other gases include carbon dioxide (an average of 200 million tonnes a year), sulphur dioxide, which can corrode aircraft, and hydrogen sulphide, which is toxic.

A long period of inactivity and highly viscous **magma** causes such a solid plug to grow in the **vent** of a volcano that highly-gas-charged lava eventually explodes sideways out of a weakness in the flank of the volcano in a primary hazard known as a **nuée ardente**. A very hot, incandescent cloud, composed of gas and tiny fragments of solid material, moves very rapidly down the slope, keeping contact with it. Its temperature can reach 1000 °C. Only two people out of 30 000 survived when a nuée ardente rolled down on to the capital town of St Pierre from Mt. Pelée on Martinique in the Caribbean in 1902.

Fig. 9.13 The crater of Stromboli emits gases frequently, stopping their build-up and preventing violent eruptions

Liquids

Lava is both the liquid material that flows out of the crater of the volcano and the rock it forms when solidified. It originates from magma, molten rock beneath the surface, which rises from a **magma chamber** beneath the volcano through a **vent** to reach the surface. The most dangerous **lava flows** are runny basalts, which occur at constructive plate margins and oceanic hot spots. As they can move at 50 km an hour, anything in their paths is rapidly covered. The fastest basalt lavas are of the **aa** type, formed when a lot of lava erupts quickly. **Aa lava** is thick, up to 10 metres deep, with a surface that breaks into rough clinkers as it moves. Its steep sloping front moves forward as a unit, with sudden, dangerous surges of speed, destroying anything it touches.

Slower-flowing **pahoehoe** lava is less than two metres thick because it forms when low volumes are ejected more slowly. As it solidifies while moving, its smooth surface has curved flow lines, giving it a rope-like appearance. It flows in individual lobes, moving around obstacles, setting flammable objects on fire as it does so. As it is less viscous than aa lava, it cools more slowly and flows further.

Fig. 9.14 This aa lava flow in Lanzarote buried eleven villages and blocked roads

Fig. 9.15 This high, steeply-sloping front of a basalt and obsidian lava flow moved down a valley from Newberry volcano, a shield volcano in Oregon USA, and created a lake by impeding drainage

Fig. 9.16 Ash and cinders piled on top of older pyroclastic material on the lower slopes of Lava Butte

Solids

Pyroclastic material is solid particles that reach the ground in pyroclastic falls (airborne pyroclastic material is also known as **tephra**). Some of it is the shattered remains of the plug that solidified in the vent after the previous eruption. Other pieces form when molten lava solidifies while in the air. Solid materials are categorised by their size and shape: **ashes,** the smallest, are less than 4 mm in diameter while **cinders** are about 4 to 5 mm in diameter and **lapilli** are pebble-sized. **Volcanic blocks** are large angular fragments resulting from the shattering of solid lava during an eruption, whereas **volcanic bombs** are rounded because they form as molten lava cools while spinning through the air.

All ejections of pyroclastic material can be dangerous, as it is usually hot. It is also heavy and even ash can cause roofs to collapse and damage crops, machinery, electronics and people's lungs. Heavier particles, such as bombs, usually fall to the ground within 3 km of the vent, but the lighter particles can rise high into the atmosphere where they can damage aircraft engines. The enormous ash cloud emitted by Eyjafjallajökull in 2010 drifted over Europe from Iceland and disrupted flights for more than a week. More than 100 000 flights were cancelled, costing airlines almost $US 2.5 billion.

When lava domes collapse, hot, dry rock fragments and gases move rapidly away from the vent down slopes and valleys by gravity. These **pyroclastic flows** kill almost half the people who die as a result of volcanic eruptions. Their highly destructive nature results from their high density, fast speed of travel (80 km/hr to 100 km/hr commonly), long distances covered and intense heat (usually 200 °C to 700 °C). The density of materials is lowest at the top of the cloud and greatest in its base flow, which means that the densest part containing boulder - sized fragments moves in contact with the ground and destroys everything with which it makes contact. Above the base flow hot gases keep the ash fragments buoyant. The heat sets nearby buildings, forests

Fig. 9.17 Cinders, volcanic blocks and bombs on the upper slopes of Lava Butte

and crops on fire and people and animals on the edges of the flows die from breathing in the hot gases. Wide areas are buried by hot pyroclastic debris up to 200 m thick that often welds together. If loose, it can provide material for equally hazardous lahars to occur if water is added to the deposit.

Nuées ardentes, described earlier, are categorised as a special type of pyroclastic flow, being characterised by their incandescent ashes that glow in the dark.

Types of volcano

Cinder cones

Cinder cones form when blobs of gas-charged lava are thrown into the air and break into fragments. The inappropriately-named Lava Butte in Oregon is an example. During its growth it blocked and diverted the Deschutes River.

Shield volcanoes

These are formed of basic lava, containing less than 50 per cent silica. Consequently, it is fluid, flows long distances and solidifies slowly. If it issues from fissures, it forms extensive plateaus, like the Deccan in India, but shield volcanoes result when there is a central vent. These volcanoes are enormous, with very wide bases and gentle slopes of about 5°.

Shield volcanoes form mainly along constructive plate margins - for example in Iceland, which has built up above sea level by layer upon layer of lava. Mauna Loa in the Hawaiian Islands, the largest active volcano in the world, is an example formed at a hot spot - a plume of molten material from the mantle, ejected at the surface far from a plate boundary. From the ocean floor to its summit, it rises 9000 m, which is greater than Mount Everest's height above sea level.

6. Comment on the number of volcanic cones in Fig. 9.14 and suggest why this results from the formation of Lanzarote at a hot spot.

Stratovolcanoes

Stratovolcanoes form at convergent (destructive) plate boundaries where the magma gains added silica as it rises though continental rocks. As the lava is intermediate between acidic and basic, it is more viscous than that of a shield volcano, resulting in steeper sides, which usually steepen towards the summit, giving a concave slope overall. The base is narrower than that of a shield volcano.

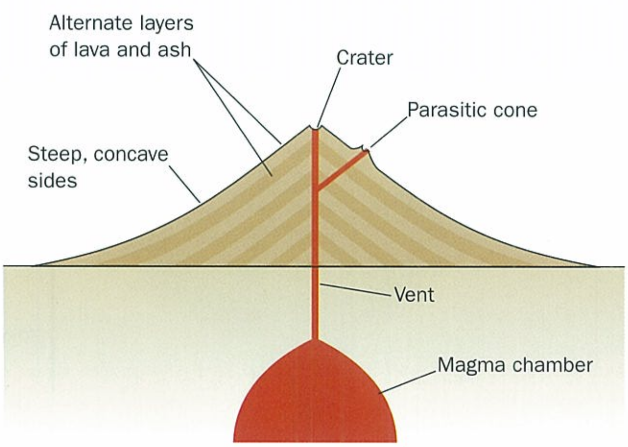


Fig. 9.18 A cross-section through a stratovolcano

Stratovolcanoes are particularly dangerous because they have long dormant periods, so people are not always convinced that they should heed warnings to evacuate. During dormancy a thick plug of solidified magma builds up in the vent and, as the magma has a high viscosity, a considerable amount of pressure has to build up to unblock the vent, usually culminating in an explosion which shatters the plug into pyroclastic fragments, followed by outpourings of lava.

Parasitic cones form on the sides of volcanoes when the main vent becomes blocked and the magma finds another way out.

Fig. 9.19 Orsorno, a stratovolcano in Chile. Note the small parasitic cones in the form of lava domes on each flank and glaciers at the top, which could lead to flooding and lahars during an eruption

Fig. 9.20 Since Mount St Helens erupted in 1980, a lava dome has developed in the crater. Gases are rising from the back edge of the dome and thick lahar deposits are seen in the foreground

Lava domes

These relatively small domes, with steep sides and rounded tops, can form on the slopes of, or in the craters of, stratovolcanoes. They are composed of silicic lava (containing more than 60 per cent silica) which is too viscous to flow far, so it solidifies quickly, forming a thick crust. Domes swell as they grow from within. Very explosive eruptions result when they collapse. Mt Pelée in Martinique developed a lava dome before its 1902 eruption.

Types of eruption

Volcanoes are classified by the nature of their eruptions.

- Icelandic – fluid basalts issue quietly from fissures at mid-ocean ridges.
- Hawaiian – fluid basalts issue from vents in volcanoes. Gases escape easily and quietly with occasional spurts of gases from lava lakes causing lava fountains.
- Strombolian – less fluid lava and gases escape with moderate explosions in which lava bombs are ejected. Stromboli is known as 'The lighthouse of the Mediterranean' because of its very frequent activity.
- Vulcanian – eruptions are more violent because the more viscous lava solidifies more quickly and traps gases. Ashes and cinders are emitted when pressure is released. Dark, ash-laden clouds rise to form a cauliflower shape.
- Vesuvian – the viscous magma gains a high gas content during long periods of inactivity and a deep plug forms, which can only be blown off after considerable pressure has built up. The violent eruption sends a wide, dark ash cloud into the stratosphere. Ash falls over a wide area. The AD 79 eruption of Vesuvius buried the town of Pompeii under 25 m of tephra.
- Plinean – a very violent explosion of gas, ash and pumice results in a narrower cloud that extends into the stratosphere. The high ash cloud from Mt Pinatubo's 1991 eruption (Fig. 9.54) circulated the world several times in the stratosphere, causing temporary global cooling of about 0.5 °C.
- Peléan – highly viscous magma and a long period of inactivity cause an explosion out of a weakness in the side of the volcano, with a nuée ardente falling down the slope.

Volcanic explosivity index (VEI)

This scale from 0 to 8 is logarithmic like the Richter scale.

Eruptions of VEI 4 and above send materials into the stratosphere and are capable of global cooling. The largest eruption in historic time was Tambora, Indonesia, in 1815, with a VEI of 7.

VEI	Volume of material ejected	Eruption frequency	Plume height	Example
1	>10 000 m³	daily	up to 1000 m	Stromboli
3	>10 000 000 m³	few months	3–15 km	Nevado del Ruiz
5	>1 km³	about 10 years	20–35 km	Mt St Helens
7	>100 km³	about 1000 years	>40 km	Mt Mazoma
8	1000 km³	about 10 000	>50 km	Yellowstone

Table 9.6 Examples of eruptions classified by the volcanic explosivity index

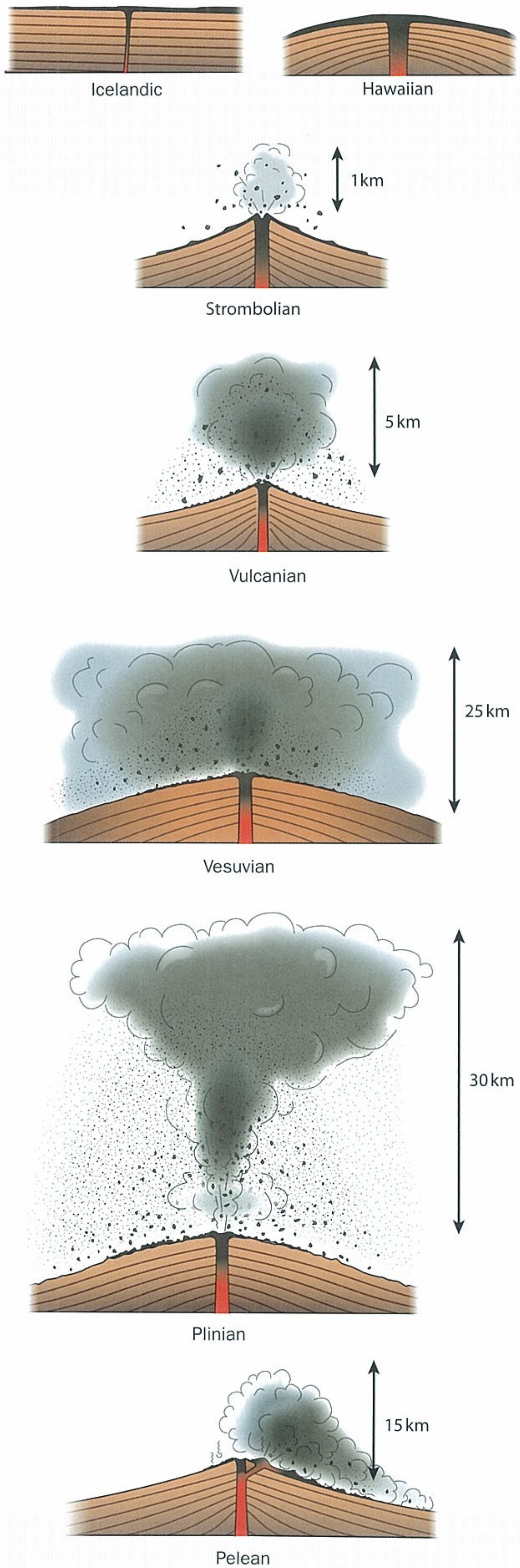


Fig. 9.21 Types of eruption

Secondary volcanic hazards

Secondary hazards result from the primary hazard and usually affect a wider area.

Fig. 9.22 Crater Lake in Oregon, formed by the eruption of Mt Mazoma 7700 years ago. The summit collapsed into the magma chamber leaving a **caldera** 8 km in diameter and 1.6 km deep, that filled with rainwater to form the lake

Lahars

Theses volcanic mudflows form when water mixes with loose pyroclastic material, with particle sizes varying from small debris to boulders, forming flows resembling wet concrete down the slopes of volcanoes and into valleys beyond them. The source of the water can be the intense rainfall accompanying the eruption, glacier melt, snow melt or dam failure. Lahars are dense and viscous but flow very fast, reaching speeds of 75 km an hour. The more volcanic material they contain, the faster they flow and the more destructive they are. They are most common on the steep slopes of stratovolcanoes where the downward pull of gravity is strong but can occur on shield volcanoes, as in Iceland. They quickly increase in size as they gain more water and erode more material to carry, but die out as they move away from the volcano.

Volcanic landslides

These masses of rock and soil moving downslope under gravity can be dry or wet, although they are drier than lahars. With the addition of water as they flow, they can transform into lahars if they contain more than 3 per cent fine clay particles. The landslides originate as large slabs of rock but disintegrate into progressively smaller particles as they move downslope. A volcanic landslide can as huge as 100 km^3 in volume and faster than 100 km/hr. Their great size and speed enables them to rise over ridges, as occurred when the north face of Mount St Helens collapsed during the 1980 eruption. The resulting landslide crossed a 500 m high ridge, 5 km from the crater.

Volcanic landslides result when magma forces its way to the surface and pushes outwards, causing the rock to break or over-steepen and collapse by gravity down the high, steep sides of the stratovolcano. They can also be triggered by large earthquakes beneath a volcano.

In turn, volcanic landslides trigger volcanic explosions by removing the 'lid' on the gases and rising magma. They bury valleys and, after coming to rest, cause lahars as water drains down-valley from them. The fastest flow of the Mount St Helens lahars was five hours after the landslide stopped moving and they travelled 55 km further than the landslide. Landslides that do not stop moving but change gradually into a lahar can travel more than 100 km and are the most hazardous.

When landslides block tributary valleys they impound lakes, which can suddenly break through the natural dam and cause further lahars. A large landslide on the coast of Kyushu Island, Japan, in 1792 resulted in a tsunami, causing 15 000 deaths.

Volcanic hazards and factors influencing them, at different types of plate boundary

Conservative margins have little vertical movement and lack volcanic activity but earthquakes result from horizontal movements.

Plate boundary locations	**Divergent/constructive plate boundaries** (e.g. in Iceland) and **oceanic hot spots** (such as Lanzarote, Galapagos Islands and Easter Island)	**Convergent/destructive plate boundaries** (especially along the Pacific Ring of Fire)
Types of volcano	Shield volcanoes	Stratovolcanoes and dome volcanoes
Magma/lava	It erupts on the ocean floor, so is mafic (e.g. basalt), basic and fluid.	It rises through silica-rich continents so is more silicic (e.g. rhyolite, andesite), acidic and viscous.
Other emissions	Effusive: lava flows with fire fountains and ash flows. Routes followed depend on gravity, relief and the viscosity of the flows.	Explosive: pyroclastic flows, nuées ardentes and ash affect wide areas.
Secondary activity	Floods. Occasional big ash clouds disrupt air traffic (e.g. Iceland 2010).	Lahars, global cooling from atmospheric ash clouds, floods.

Table 9.7 Volcanic hazards at divergent and convergent plate boundaries.

Case study: Nevado del Ruiz, Colombia (an LIC), November 1985

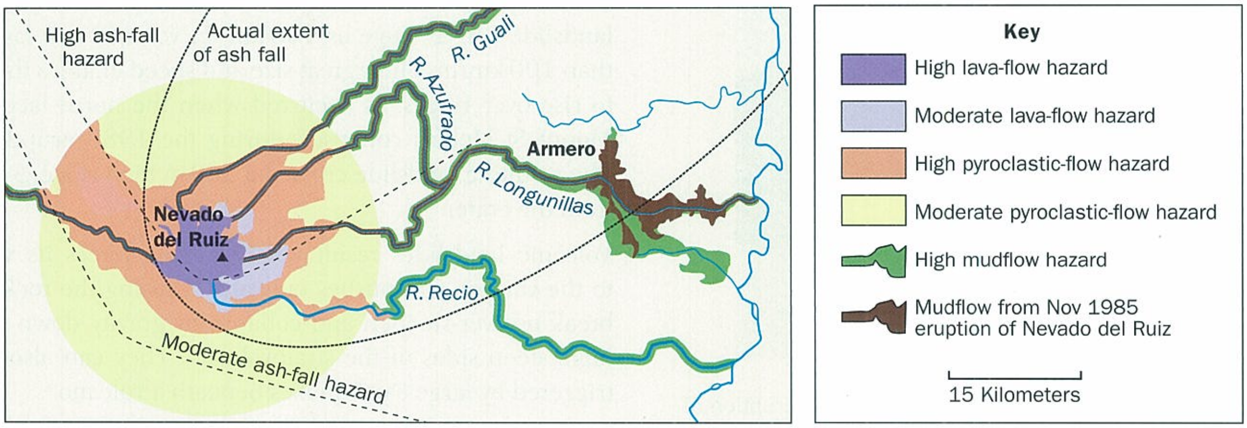


Fig. 9.23 Nevado del Ruiz hazard map

This stratovolcano in the Andes results from the oceanic Nazca plate subducting beneath the South American plate.

Prediction and monitoring

- September 1985 – a **hazard map** was drawn up showing locations in danger from ash and rock falls and lahars, including the dangerous location of the town of Armero but many people remained unaware of it, as the map was not well-distributed.
- October – scientists warned of a great risk of lahars and advised local authorities to prepare for an evacuation.
- November 13 – seismographs registered strong earthquakes but the people monitoring them failed to recognise the warnings.

The eruption hazards

- Ash eruptions started at 15.00 on 13 November but, as they stopped after four hours, people were told to stay indoors rather than to evacuate.
- Soon after 21.00h, a 30 km high ash cloud shot up. Civil defence workers tried to warn officials in Armero but failed to make contact. People in the town were advised locally there was nothing to worry about.
- The eruption melted the summit snow and glaciers, causing thick lahars to race down narrow river valleys at about 60 km an hour, making river volumes four times larger.

Effects on lives and people

The first lahar, boosted by water from a lake that it passed through, hit Armero only two and a half hours after the eruption. Others quickly followed, including one 30 m deep. People were suffocated by the mud and crushed by collapsing buildings. The eruption caused 23 000 deaths (20 000 in Armero), the second highest from a volcanic eruption in the 20th century after Mt Pelée, and the highest caused by lahars.

Rescue efforts were slow because the mud was very deep and it was impossible to move across it without sinking in. Also, roads and bridges leading to Armero had been cut. Hospitals were overwhelmed and some people died because of the lack of antibiotics to treat infected wounds. The tragedy cost the country $US 7 billion.

Risk perception

Nevado del Ruiz had been dormant for 69 years and, as there had been no significant eruption for 140 years, officials were reluctant to take expensive prevention measures. Inadequate preparation was the main reason for the deaths, together with a failure to act promptly when it was clear that an eruption was imminent. Also, at the time of the eruption the government and army were busy dealing with a civil war.

Case study: Mount St Helens, USA (an HIC), May 1980

The magma supplying this stratovolcano results from the subduction of the Juan de Fuca plate beneath the North American plate. The amount of ash ejected by Nevado del Ruiz was only 3 per cent of that from Mount St Helens in 1980. Mount St Helens also produced the biggest volcanic landslide in historical time.

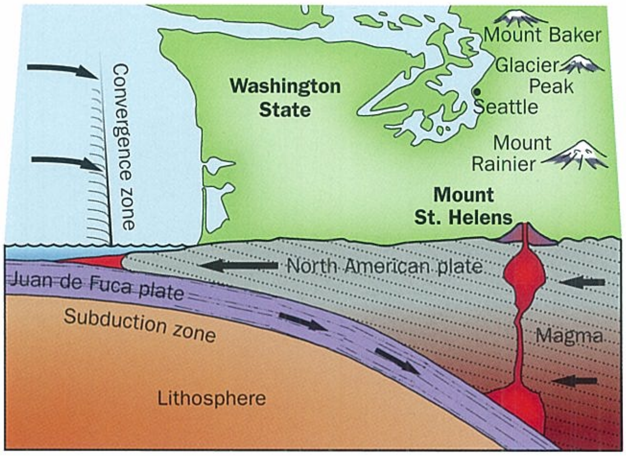


Fig. 9.24 The location of Mt St Helens

Prediction, monitoring and perception of risk

The US Geological Survey keeps volcanoes in the country under close observation. They draw up hazard maps and monitor gas emissions. Ground deformation was monitored using lasers in 1980, but is done by GPS now. Many seismometers record the magnitude of earth movements, sending the measurements direct to the University of Washington Geophysics Laboratory. These enable fairly accurate predictions of eruptions.

In March 1980, shallow earthquakes on the north side of the volcano were recognised as being different from the thousands that occur every year. The **harmonic tremor** of continuous rhythmic earthquakes often precedes volcanic eruptions, so extra seismographs were installed and emergency services, guided by the hazard maps, worked on plans to evacuate. Ash eruptions followed for a few weeks and the north flank of the volcano started to bulge. People were not allowed within 13 km of the summit. Most property owners moved away and emergency evacuation plans were made for communities further down the valleys. By the end of April the bulge had grown into a sizeable dome.

The eruption hazards and their effects on lives and people

- On May 18 the north flank broke open and, with the summit of the volcano, fell downhill as a massive rock landslide 2.3 km^3 in volume. It left a new horseshoe-shaped crater, 2 km wide, 3 km long and 600 m deep, open at the north end. (Figs 9.20 and 9.26.) The powerful landslide was channelled down valleys and swept over ridges. Most of the rock was deposited in the North Fork Toutle River Valley (Fig. 9.25).

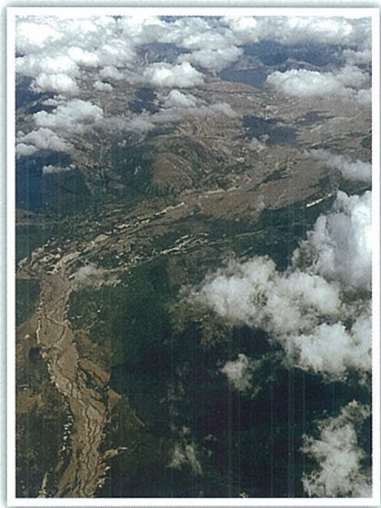


Fig. 9.25 Lahar material in the North Fork Toutle River Valley in 2013. The summit of Mount St Helens is at the right top of the photograph

- When the landslide stopped moving 22 km from the volcano, its water content, together with melted snow and ice from the glaciers on the slopes of Mount St Helens, rose to its surface and mixed with loose rock material to form destructive lahars, which ripped out eight bridges and cut evacuation routes.
- So much debris reached the Columbia River that ocean-going ships could not sail on it because the previously 200 m wide, deep channel was reduced to less than 70 m wide and 3 m deep.
- Immediately after the landslide, an enormous cloud of gas, rock, ash and ice blasted laterally and

upwards. Hot pyroclastic flows drained rapidly down the volcano's sides, spreading over and beyond the landslide to cover 550 km^2.

- Helicopters rescued more than 100 people. Only 57 died, including a geologist monitoring the hazard and people who refused to leave the area.
- Ash had to be cleared from roads.
- People suffered from post-traumatic stress disorder for years afterwards.

7. Compare and contrast the main effects of the eruptions of Nevado del Ruiz and Mount St Helens in a table. To what extent are differences explained by the different levels of economic development of the countries?

Fig. 9.26 The north flank of Mount St Helens 33 years after the eruption. The landslide rode over the ridge where the photograph was taken. The North Fork Toutle River Valley is to the right

8. (a) Use Fig. 9.26 to draw a diagram to show the shape of the summit area of Mount St Helens after the eruption and add a pecked line to show its likely shape before it.

(b) The lahar covers the foot of the north flank of the volcano at the headwaters of the North Fork Toutle River. Describe the appearance of the lahar material now and explain why it is different from when it was first deposited. Why is its presence a continuing hazard?

Primary and secondary impacts of tectonic hazards on lives and property

Primary impacts are the immediate results of an earthquake shockwave or of a volcanic eruption; **secondary impacts** happen after the shockwaves or eruptions have finished and are the consequences of the primary impacts. Some continue for a long period.

Factors influencing the amount of damage caused by the shockwaves of an earthquake

- Amount of energy released, indicated by the Richter scale.
- Depth of the focus - the shallower the focus, the greater the effect. The rocks above absorb some of the energy of deep-focus earthquakes.
- Number and strength of foreshocks and aftershocks. Buildings weakened or damaged by one earthquake may collapse when further damaged by another.
- Distance away from the epicentre. As the distance increases, the strength of the shockwave decreases.
- Nature of the bedrock. If it is solid, damage is limited but where the rocks are weak or loose sands or clays, liquefaction can occur. It can be very destructive, particularly on a slope.
- Population and building density at or near the epicentre. (The above factors are insignificant unless an area is populated.)
- Strength and type of the buildings. Modern buildings in earthquake zones in economically developed countries are usually strengthened against earthquake damage.

The time of day is also significant. During the night there will be fewer deaths in strongly-built homes than at rush hour when people on the streets are likely to be hit by falling masonry. More people are out of their homes during weekdays than weekends. Deaths also depend on risk perception, which leads to the amount of preparation by the population and by emergency services before, during and after the event. This is greater in HICs than LICs, where funding is a problem.

Managing earthquake hazards

Earthquake prediction

The New Zealand Earthquake Commission predicts a major earthquake will happen in Christchurch every 55 years. It is not possible to predict exactly when an earthquake will occur or where its epicentre will be. Short-term predictions cannot be made. Most major earthquakes will occur along plate boundaries as a result of a cycle in which strain builds up and is eventually released. The average movement of plates, usually a few millimetres a year, has been calculated but it is not known exactly where in the cycle a particular location is.

Geologists use the **seismic gap theory** to work out where a strong earthquake is likely to occur. 'Gap' refers to the section of an active fault that has not experienced earthquakes for a considerable time compared with other segments along that fault. All parts of the fault are expected to experience the same degree of displacement over time. The location of the 1989 earthquake in the San Francisco Bay area along the San Andreas fault was at a known gap. Using past records, the frequency of earthquakes along part of a fault is calculated to predict the next one and the rate of movement of sections along the fault is also used. The longer the period without an earthquake, the greater the accumulated stress and the greater the likelihood of a strong earthquake.

Monitoring of earthquake zones

A lot of money has been spent in monitoring, using very expensive instruments, particularly along the San Andreas fault in California, USA.

- Horizontal movements are detected by measuring the change in the time it takes a laser beam to move between two fixed points on either side of a fault.

Event	Primary impacts	Secondary impacts
Earthquake	Deaths, injuries, panic and shock caused by collapsing bridges and buildings. Roads are destroyed as vertical movements cause fault scarps to develop or the ground is offset horizontally.	Soil liquefaction, caused by shaking, leads to buildings sinking. Homelessness, lack of shelter and loss of livelihoods occur. People living in temporary tented accommodation or sleeping outside in areas with cold winters or very cold nights can die from hypothermia. Water often becomes contaminated with sewage, leading to disease. Fires and lack of power are caused by the destruction of electricity cables and gas pipes. Water shortages and thirst result from broken water mains. Breakdowns in telephone and internet communications, mudflows, landslides and tsunamis can occur. Famine can be a long-term effect. Theft and other crime can result.
Volcanic eruption	Lava flows, ash and tephra falls, pyroclastic flows, release of gases and nuee ardentes.	Lahars, landslides, tsunamis from undersea eruptions, crop damage and famine, loss of homes and livelihoods, disruption to flights where ash clouds occur, long-term cooling of the atmosphere.

Table 9.8 A summary of primary and secondary impacts resulting from tectonic hazards

- Changes in slope are detected by a tilt meter, which is like a very sophisticated spirit level.
- Variations in the Earth's magnetic field, resulting from changes in stress in the rocks, are measured by a magnetometer.
- Seismograph records are monitored. Clusters of small earthquakes often precede a large one.
- The amount of radon gas rising to the surface is measured, as it can increase before an earthquake.

Many scientists think reliable prediction will be impossible.

Hazard mapping

Hazard mapping is undertaken to show areas of ground that are likely to liquefy, fault locations and dates of past movements, past earthquake epicentres with magnitudes and dates and areas where landslides and tsunamis might result. After the 2008 earthquake in Sichuan, which destroyed a school built on a fault, geologists started searching for fault locations to map them as unsuitable locations for development. Ground movements leave earthquake scarps, which need to be mapped, but this vital evidence is often quickly removed by erosion and landslides. However, the authorities in Sichuan could not wait for the maps to be completed before they rebuilt and the replacement buildings are not strong enough to survive an earthquake of the same magnitude. There are now many vulnerable large cities in earthquake belts in China.

Hard engineering

Engineer geologists know what infrastructures need replacing, moving or strengthening. It is cost-effective to make the necessary changes rather than meet the expense of restoration after a strong earthquake.

Strengthening buildings

There is little space for building in mountainous Japan, so skyscrapers are built in a pyramid shape for strength. Unfortunately, such measures do add to the cost and builders in some countries make profit, not building regulations, their aim. Even poor rural areas can have safer buildings, using thatch for roofs and mud and straw for walls.

Land-use zoning

Land uses, such as oil storage depots, that are potential fire or explosion risks are positioned away from homes, and are built on solid rock. Land likely to liquefy is used for playing fields, nature reserves and parks, not buildings.

Increasing risk perception

Earthquake drills allow people to practise what to do in an earthquake and are regular events in schools and workplaces in many tectonic areas. Japan holds an Earthquake Awareness Day each year so everyone will be able to follow emergency procedures without panic.

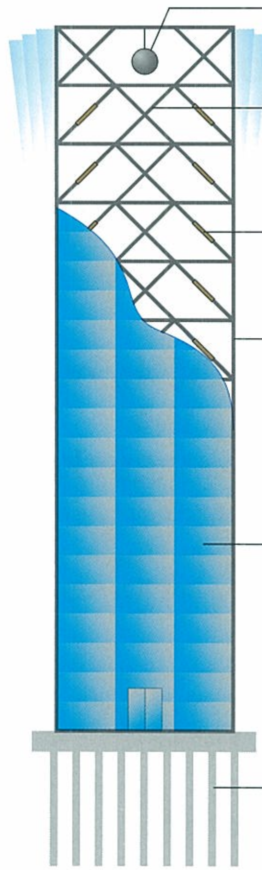


Fig. 9.27 Earthquake-proof building methods in Japan

Evacuation points, with water, food and medical supplies, are placed in every neighbourhood. People are given maps of routes to follow and leaflets about how to dress and what to take. They are informed how to improve safety in the home, such as by securing furniture to the walls and knowing how to switch off the gas supply. In Japan, gas supplies automatically shut off in an earthquake to reduce the fire risk. People are advised to keep a survival pack near an exit and to have food and drink available to last at least three days.

Predicting, hazard mapping and monitoring of the tsunami hazard

When a seismic event is detected that could cause a tsunami, a tsunami watch starts. Sea level height detectors confirm if one has been generated. An International Tsunami Early Warning System, operated by NOAA in Hawaii, covers the Pacific Ocean. Seismograph stations and tidal stations spread across the ocean send automatic warnings to Hawaii as soon as the water reaches a certain height. Satellites monitor the tsunami as it crosses the ocean. Communications systems at threatened coasts, warned by the centre in Hawaii, make residents aware of

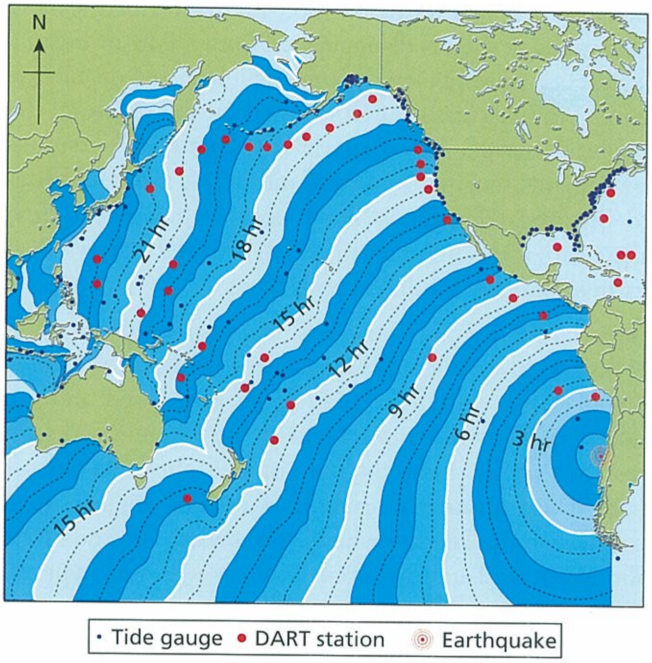


Fig. 9.28 Isoline map showing travel times of the tsunami wave following the 2010 Chile earthquake

the impending danger by various methods, including text messages, and evacuation procedures are put into place. After the 2004 tsunami, an international warning system was set up for the Indian Ocean.

9. Use Fig. 9.28 to state how much warning of possible tsunami danger could be given to San Francisco, New Zealand and Japan after the 2010 Chilean earthquake.

Managing volcanic hazards

Predicting and monitoring volcanic eruptions

Remote sensing by satellite sensors detects deformation of the ground surface and temperature changes caused by heating in the ground before an eruption. Gravity meters on the ground detect gravitational changes due to magma movement. Geochemical changes are also indicative of an impending eruption. Thermal waters, such as hot springs on volcanoes, have increased levels of CO_2, H_2 and He dissolved in them before an eruption. Chemical sensors also measure increased sulphur levels.

Action taken during eruptions as a result of risk perception

In Iceland and Hawaii cold water was hosed on to lava flows to cool them and reduce their flow length. On Etna lava flows were bombed and diverted away from settlements by channels and in 1992, when the town of Zafferana was threatened, large concrete blocks were dropped into the lava tube from which the lava was flowing. It stopped before reaching the town.

Case study: Portland, Oregon, USA – Living with tectonic hazards

The city of Portland developed before seismic gap theory predicted it is likely to experience a magnitude 9.0 earthquake, during which few of its present buildings, bridges, roads and services would escape severe devastation. A map has been published showing the large areas of the city built on ground likely to liquefy and also where **landslips** are a known hazard. The School of Civil and Construction Engineering at Oregon State University is coordinating a programme with representatives of the vital services – transport, gas, electricity and water – to prepare the city. Engineer geologists have begun a race against time to research, plan and undertake hard engineering to hold back steep slopes adjoining main roads and to strengthen structures, such as bridges, where it is cost-effective to do so. Others are likely to be rebuilt away from faults and ground prone to liquefaction. Buildings will need very deep foundations. The whole process could take fifty years.

Public awareness is spread via the media, public meetings and information packs for households about how to prepare for an earthquake and the action to take if one occurs.

Three active volcanoes, Mt Hood, Mt Adams and Mt St Helens, are near but this combination of tectonic hazards does not stop businesses and people from relocating to Portland.

People live near tectonic hazards for a variety of reasons:

- the hazard may not have been predicted
- people may be unaware of the danger if the volcano is dormant or there has been no large earthquake in recent time
- they are reluctant to leave their place of birth, family or friends
- their perception of risk is that it will happen to others but not to them, so they do not accept that they need to take action to reduce risk. People interviewed after a hazard often comment that it is something that happens elsewhere but was not expected to happen to them
- some, such as the Afghan people, take a fatalistic attitude that the hazard cannot be controlled, so it has to be accepted

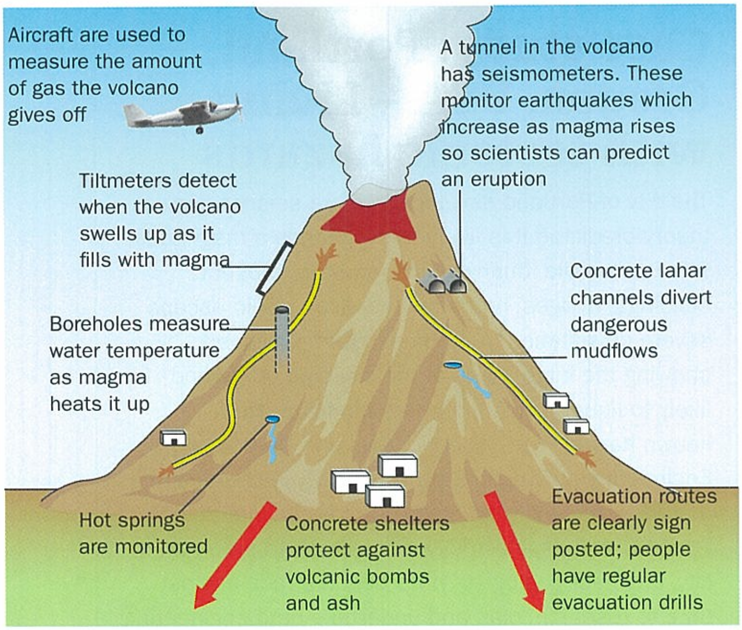


Fig. 9.29 Some ways in which volcanic hazards are reduced

→ economic reasons, as people are reluctant to leave their jobs. Sulphur is mined from active volcanoes and basic lavas weather to fertile soils suitable for intensive agriculture, as on the densely populated island of Java. Geothermal energy in volcanic areas leads to industrial developments and cheap heating for homes and for crops grown in hothouses, as in Iceland. The dramatic volcanic landscape attracts tourism, which encourages population growth. For such reasons, people believe that the benefits from living in a hazardous area will be greater than the costs of doing so.

Hazards resulting from mass movements

Mass movements and resultant hazards: nature and causes

The physical and human causes of types of mass movements are described in Chapter 3. A mass movement which affects people and their property is a hazard, especially when it is unexpected and large-scale but even a single rock fall can be hazardous. Human mismanagement is a prime cause of slope instability.

Types of hazardous mass movements

Movement is mainly through the air in rock and debris **falls**. **Slides** and **flows** move on the surface both downward and outward. The more rapid ones are the more hazardous. A slide is distinguished from a flow by being a solid mass moving along a single failure plane or fracture zone. Further classification is based on the nature of the material moved. Dry material can produce hazardous movements ranging from rock and debris falls and slides to **slumps**. Hazardous flows occur when earth (fine material) or rock (coarser material) is mixed with water to form earthflows, mudflows and lahars.

Both landslides and landslips (slumps) occur in solid rocks and in weathered material. In a landslide, the plane along which movement takes place is inclined and the material moves in a mass, breaking up where it comes to rest. In a slip or slump the movement is rotational along a curved **slip plane** and results in an arcuate slip face and a relatively unbroken **toe** which rises towards the end of the slipped mass. Landslips occur in areas with rock types of different permeability.

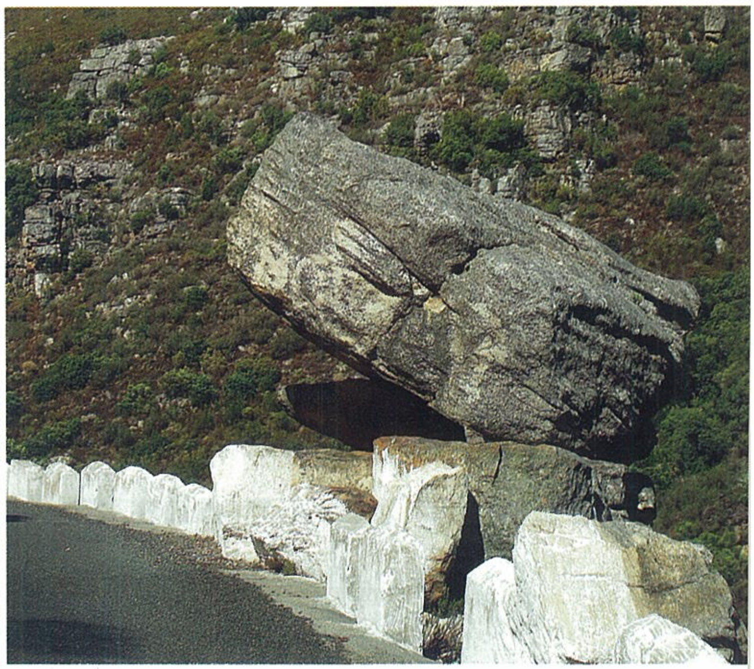


Fig. 9.30 Rock falls from cliffs are localised hazards along mountain roads

Fig. 9.31 A small debris slide in the Peruvian Andes

Case study: Mam Tor Landslips, UK

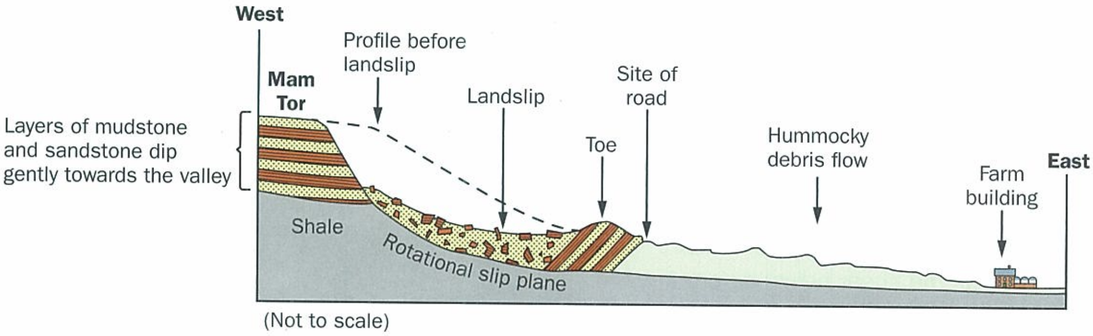


Fig. 9.32 Diagrammatic cross section through the mass movements at Mam Tor

Mam Tor is believed to have the largest landslip (slump) in Europe. It has totally physical causes: the mountain is composed of alternating permeable sandstones and impermeable shales which dip slightly towards the valley. The shales (very finely bedded mudstones) can be crumbled easily by a person's hand, so have very little strength. Their upper layer becomes slippery when wet and provides a lubricated layer for the rock above to slip down over it. About 3000 years ago, water saturated the sandstone beds adding weight, until the stress was so much that the rock mass broke along, and slid down a rotational concave slip plane. It left a 70-metre-high slip face with a typical arcuate shape and an up-tilted toe at its foot. There have been many slips since and they still occur. The most significant one was a hazard in 1979 when the major road between the cities of Sheffield and Manchester, which crossed the toe of the slip and had been repaired many times after smaller slips, was cut and abandoned, as it was no longer economic to repair it. Heavy vehicles now have to take a long detour.

The large scale of the slip is evident in Fig. 9.33. Each layer of the exposed remains of the road represents a repair after a slip. At least five are visible and in places the repairs are two metres thick. Broken shale is seen in the centre left where the material is still slipping, aided by a spring, which issues where the brown vegetation is. Wet shale is very slippery, so layers above easily slide over wet layers below them. In the face of the scar, composed of thin beds of permeable sandstone and shale, small mudflows indicate where the wet shale has turned back to the mud it once was.

Below the toe is a hummocky debris flow consisting of material from the landslip, which threatens to bury farm buildings in its path. The landslip and debris flow together are more than a kilometre long. The average flow movement is 250 mm per year, but is faster in wetter years. Recent research revealed that it has moved continuously by up to 500 mm per year since its formation.

Fig. 9.33 The slip face of the Mam Tor landslip

Fig. 9.34 The steep foot of the debris flow with the scar behind it

Case study: The Bingham copper mine landslide and rock fall

In April 2013 Bingham Copper mine in Utah, USA, experienced massive landslides when more than 135 million tons of rock and rubble moved three kilometres into the open pit. The slide was of solid bedrock that broke away from the upper half of the slope, together with waste rock from the mine that had been piled up above it, its weight putting additional stress on the slope. The rock slid down the shear plane, before free falling and flowing into the pit. The tremendous speed at which the rockslide hit the bottom caused a 2.5 magnitude earthquake.

Fortunately, slow movement in the side of the pit was noticed beforehand and sensors and radar monitored it for more than two months. The mining was stopped when movement reached 5 cm a day and the workforce was moved out of danger shortly before the landslide.

Although the landslide is thought to have been along a weak, thin, sedimentary layer within quartzite rock, possibly aided by an old fault line, it could not have happened without quarrying steepening the slope.

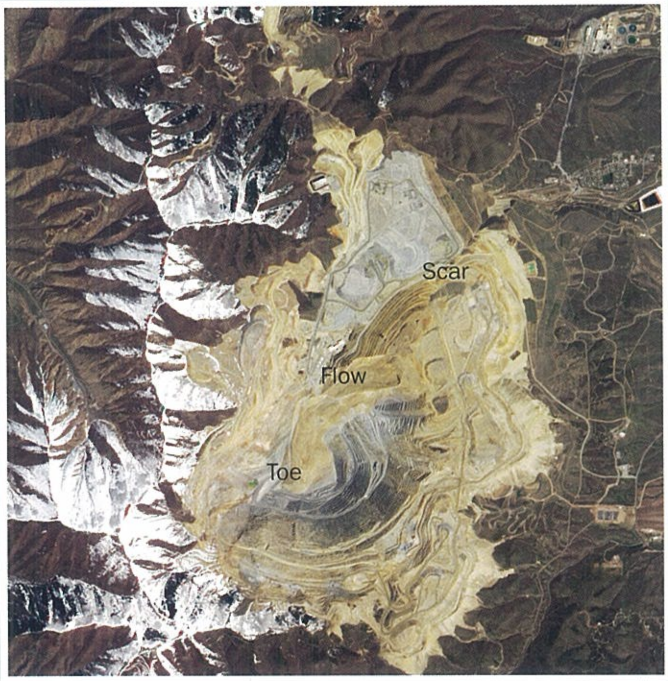


Fig. 9.36 Satellite image of the April 2013 landslide at Bingham copper mine

Fig. 9.35 The 970 metres deep Bingham Canyon Copper mine before the landslip. Excavated waste is piled up in the background

Effect on lives and property

The economic disruption made it one of the most expensive landslides, as the workforce had to be laid off while the mine was made safe. Buildings and the main access road were swept away and costly mining equipment crushed. The mining company, Kennecott Utah Copper, spent three million dollars on remote-controlled bulldozers to clear the rubble safely. Production for the year was reduced by about a half. The workforce had to be reduced, involving redundancy pay-outs. The local authority also lost a considerable amount in tax revenue, which the company would normally have paid.

This landslide shows that large rock slides caused by slope failure are predictable with considerable accuracy if warning signs are noticed and monitored. However, this slide had not been expected to fall as far as the lower part of the open pit.

Case study: Debris flows and landslides in Vargas, Venezuela

This area suffered the highest death toll from mass movements in recent times in December 1999 when approximately 30 000 people died in towns along the Caribbean coast. The actual number is unknown because many people were swept out to sea. Mass movements funnelled down steep valleys on the north side of the Sierra de Avila mountain range, which runs parallel to the coast, onto the towns below.

Factors influencing this mass movement hazard were both natural and human:

- The coastal area had become densely populated and mainly urban, despite being frequently affected by slides and flows. No one survived in the many shanty towns where flimsy shacks were easily destroyed.
- Many of the coastal towns were built on old debris flows.
- The very steep mountains behind the narrow coastal strip have many slopes steeper than the angle of repose for loose materials.
- The metamorphic rocks have planes of weakness along which landslides will occur where they are inclined towards lower areas.
- December 1999 was extremely wet, as 911 mm fell in 52 hours, equivalent to a year's average rainfall.
- The slopes had lost their protection and stability because trees had been cleared by local people.

The landslides and their effect on lives and property

Thousands of landslides triggered by the rain affected a 60 km stretch of coast. As the rock and soil slid down the mountains, added water turned them into debris flows, with high densities of rock, including large boulders, and mud. These moved very fast and were very destructive.

After the town of Caraballeda had suffered a similar experience in 1951, the channel that had been followed by the debris flow then was lined with concrete in an attempt to guide any future flow safely to sea. However, the 1999 flow left the channel at a bend and ploughed through the town, destroying houses and the first two floors of apartments. As further landslides were possible, 100 000 survivors were evacuated immediately.

All public services were lost from many areas and rebuilding has been slow. Thousands were still homeless nine years after the event and the value of surviving property had fallen by 70 per cent.

10. Comment on the degree of risk perception in the Vargas area of Venezuela in 1999.

Impacts of mass movements on lives and property

Many of the impacts on lives and property are similar to those of tectonic hazards but usually on a smaller scale, so they do not usually attract overseas aid.

11. Explain why the aftermath of a disaster is likely to be much worse in an LIC than in an HIC.

12. Describe the mass movement shown in Fig. 9.37. State the evidence for the type of movement. Explain why it was an unstable slope and the likely reasons for the movement.

Fig. 9.37 Mass movement destroying a car park built on sand and clay on the south coast of the UK

Fig. 9.38 Housing in a part of Quito, in the Andes of Ecuador, where many of the slopes are loose volcanic ash and landslips are a hazard

Fig. 9.39 This landslip near Zermatt, Switzerland, blocked 100 m of the road and only railway route from the main valley in 1991

13. Describe the effects of mass movements on lives and property.

Prediction, hazard mapping and monitoring of mass movements and perception of risk

Prediction and monitoring

Warning signs that a mass movement is likely to occur include cracks resulting from tension in buildings and in the ground, tilted structures, bulging walls and steep slopes, especially with deposited material above them. Arcuate-shaped cracks on ground above cliffs indicate the site of future slumps. Once noticed, the slopes can be closely monitored for change.

Large moving masses like Mam Tor's landslip are monitored by GPS and laser surveys to determine the amount of movement each year of a number of fixed markers on the surface of the landslip. GPS measures distance and direction very accurately. Arrows are then drawn on a map to show the direction and length of annual movements. By comparing movements with rainfall, it may be possible to determine how much water the slope can hold without moving.

Rainfall and changes in soil moisture are also monitored. Measurements in boreholes indicate changes in groundwater content and the pressure it exerts; the weight of additional water can trigger mass movements. Many drainage pipes have been placed in the Mam Tor landslip to remove water and reduce movement.

Delicate instruments such as tiltmeters, which record the amount of tilt occurring, and strainmeters, which record changes in the crustal strain to a very high degree of precision, are used in areas with active faults.

NOAA and the USGS operate a debris flow early warning system in California when heavy rain falls by monitoring areas where wildfires have removed the protective vegetation cover.

Landslide hazard mapping

Landslide hazard assessment maps are drawn up using factors that affect slope stability and knowledge of previous movements. Rocks are classified as having high, medium or low susceptibility to landslides and the degree to which they have been affected in the past is similarly classified. Maps of the routes taken by rock falls in mountain areas reduce the chances of building in their paths.

In the USA, geologist engineers are trained to recommend actions to mitigate for geological and geomorphological hazards and trained planners help local communities to undertake what is necessary to reduce the dangers. Mitigation measures are described in Chapter 3.

Perception of risk from mass movements

The degree of risk perceived varies according to distance from the site of the hazard, the amount of knowledge a person or group of people have and the length of time since a hazard last occurred. Insurance companies have a clearly defined assessment of the risk, whereas a visitor to the area may have no knowledge of risk at all. Government agencies are likely to be well informed and to take responsibility for educating the public about any risk in the locality. Private landowners also have a responsibility to inform the public about, and protect them from, any risks on their land. In the USA warnings are issued during national and local weather forecasts.

RESEARCH Explore examples of the different perceptions of people to hazards:

- Acceptance that the environment is in control and nature cannot be changed. An example is the withdrawal of protection for some coastal areas in the UK.
- Dominance – the idea that humans can provide 'technological fixes' and control the environment by engineering and technology. This was the attitude in California for a time last century when the authorities were so confident that major earthquakes could be prevented by lubricating faults with oil that they built a large hospital next to the San Andreas Fault.
- Adaptation – people perceive that they can adapt their environments to prevent hazards.

Hazards resulting from atmospheric disturbances

Global distribution of areas most at risk from large-scale tropical atmospheric disturbances and small-scale atmospheric disturbances

Hazardous **tropical cyclones** are very large low pressure systems with wind speeds of above 119 km/h and very deep low pressures, which can be as low as 880 mb. They have stronger winds than tropical storms, which have wind speeds between 63 km/hr and 119 km/hr. Tropical cyclones are called **hurricanes** in the Caribbean Sea, Gulf of Mexico and west coast of Mexico, **cyclones** in the Indian Ocean, Bay of Bengal and northern Australia and **typhoons** in the South China Sea and west Pacific Ocean. They will be referred to as cyclones within this chapter, except where a specific geographical context makes the use of typhoon or hurricane more appropriate. With the exception of the hurricanes that affect the west coast of Mexico, tropical cyclones affect the east coasts of continents and are most hazardous to the Caribbean islands and the densely-populated, low-lying coasts of Bangladesh, the Bay of Bengal and south-east USA.

Tornadoes occur on every continent except Antarctica but are most frequent in the Great Plains and eastern parts of the USA in a belt known as Tornado Alley. They can occur at any time but are most frequent in the USA between 16:00 and 21:00 hours in May and June after a long period of heating of the land.

The most disastrous tornado occurred in Bangladesh in 1989 when over 1000 people died. Tornado deaths in Bangladesh are about double those in the rest of the world combined.

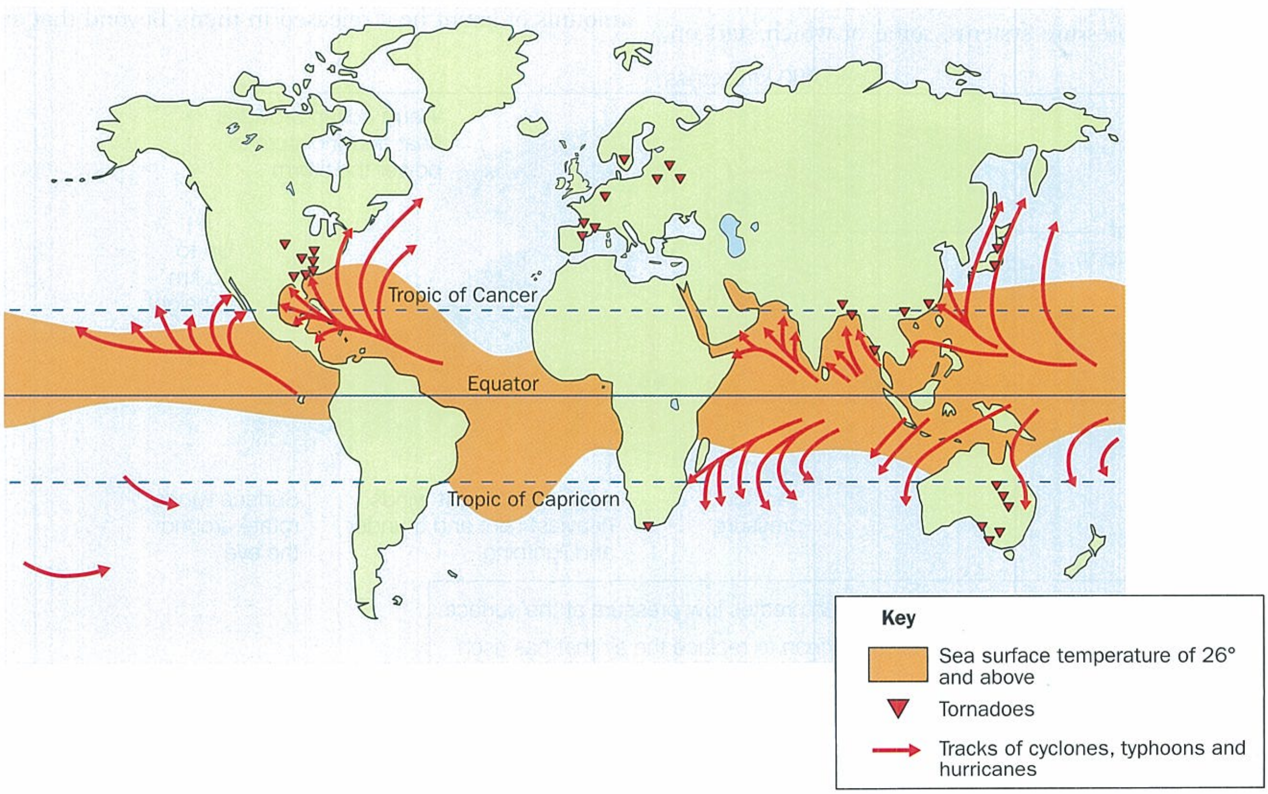


Fig. 9.40 The global distribution of large-scale tropical cyclones and small-scale tornadoes

Processes causing the formation of tropical cyclones

Having ferocious whirlpools of air, torrential rains and associated **storm surges**, flooding and landslides, tropical cyclones are very hazardous. They form over warm oceans between May and November in the northern hemisphere and between November and May in the southern hemisphere. Sea surface temperatures have to be a minimum of 26°C (according to the latest NASA figure) to a depth of at least 50 m. They form in the summer when the noonday sun is high in the sky, with maximum occurrence in late summer and autumn after a long period of intense heating. The warm sea surface is important; it warms the air in contact with it so that large amounts of water vapour evaporate into the air that moves into the storm. This moisture fuels the growth of the storm, which can only happen if the air is unstable (warmer than the air at the same height), so it will continue to rise. The heated moist air expands, becomes lighter and rises. The rise intensifies because of the added latent heat of condensation.

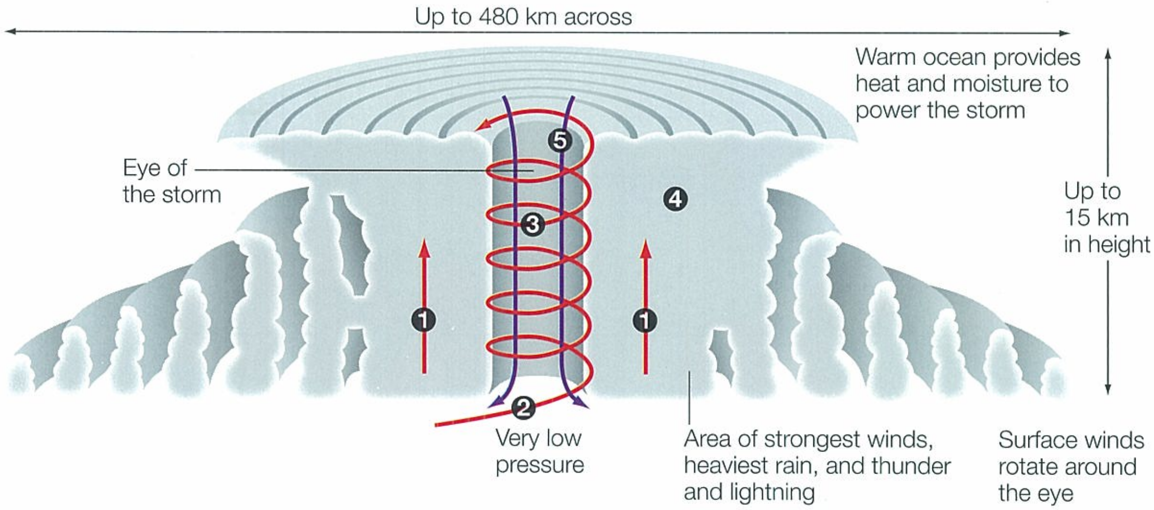
Tropical storms form only between 5° and 20° north and south. They do not form nearer the Equator because Coriolis force is needed to deflect the converging rising air into a spin and the effect of the Earth's rotation is not strong enough near the Equator. In higher latitudes the sea is not warm enough for their formation. There are no strong upper atmosphere winds in these latitudes, so the air can rise to the tropopause.

Cyclones form towards the west sides of the tropical oceans from small low pressure systems, some of which start on the east sides of the oceans and intensify as they move west. Only a few of these easterly waves develop into cyclones with winds of 119 km/h or above. Westwards air movement also results from air flowing out of the sub-tropical high pressure cells, such as the Bermuda high in the north Atlantic.

The effect of the Coriolis force can be seen in the direction of movement of the tropical storms, as they generally deflect to the right in the northern hemisphere and to the left in the southern hemisphere. However, the system is very dynamic and can alter course if very strong winds exceed the Coriolis force and change the direction of rotation. Storms gradually reduce in intensity over cooler seas and do so rapidly over land, where they lose their source of energy, water vapour intake.

These processes intensify while the system remains over warm water because, as the rising air cools to below dew point, condensation releases latent heat. This causes the air to rise even faster, the low pressure to lower even more and the moisture-laden wind to rush into the low pressure centre even faster. The lower the pressure, the more the air is drawn into it and the greater its power.

Very heavy rain falls from the thick cumulonimbus clouds produced by the uplift. At the tropopause the air cools and some sinks, forming the **eye**, a calm, sunny area in the centre of the storm. Other air moves away from the high pressure at the tropopause. A very dense circular band of cumulonimbus cloud known as the **eyewall** of the system surrounds the eye. The eyewall has the most powerful winds and deepest convection, with towering rain clouds that rise above the rest of the cyclone because of the vast amounts of latent heat released in them. Beyond that are



1. Heated, very moist air rising from the ocean creates low pressure at the surface.
2. More warm, moist air moves in over the ocean to replace the air that has risen.
3. The spiralling mass rises rapidly.
4. Thick cumulonimbus clouds are produced from which very heavy rain falls.
5. The air cools at high levels and sinks, forming the eye in the centre of the storm.

Fig. 9.41 Processes in the formation of cyclones circular bands of cumulonimbus clouds, separated by areas clear of cloud where air is subsiding into denser air, causing **adiabatic warming** by compression.

Weather in a cyclone

14. Use Fig. 9.42 to describe the changes in weather and hazardous conditions as a tropical cyclone passes over: as the eye approaches, in the eye and after the eye. Include references to time.

Hazards from large-scale atmospheric disturbances

The degree of hazard from tropical cyclones depends partly on how frequently they occur in the same area, their magnitude and the location of the area affected. The most powerful storms are not necessarily the most hazardous.

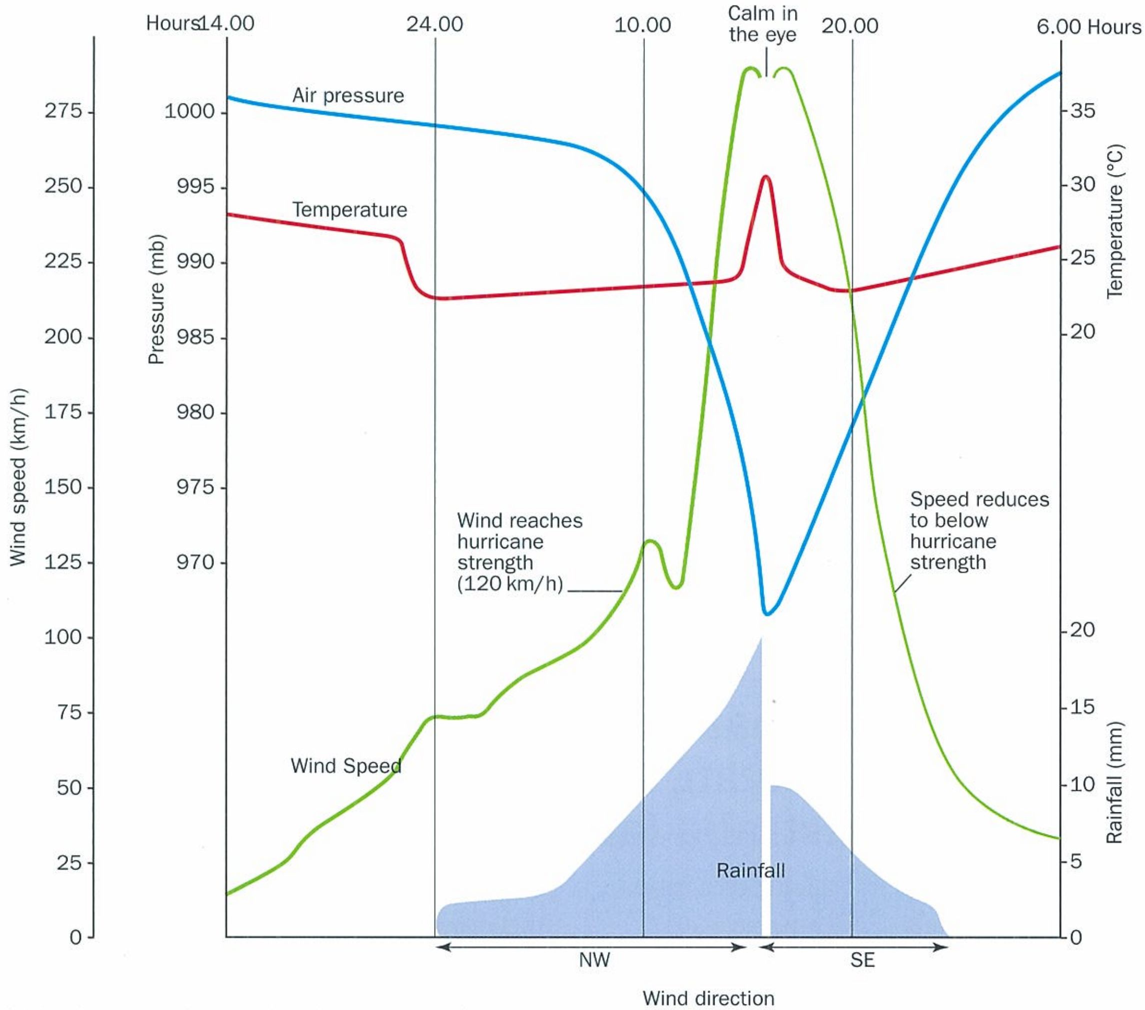


Fig. 9.42 Weather recordings during the passage of a cyclone

Category	Wind speed (km/h)	Damage
1	120–153 (very dangerous)	Well-constructed buildings could have roof damage. Large tree branches may break. Extensive damage caused to power lines.
2	154–177 (extremely dangerous)	Buildings have major roof damage. Shallow-rooted trees are uprooted. Nearly all power is lost.
3 (major)	178–208 (devastating)	Buildings have major roof damage. Many trees are uprooted or broken, blocking many roads. Electricity and water supplies are cut for several days.
4 (major)	209–251 (catastrophic)	Roofs and sides of buildings are extensively damaged. Most trees and power poles are snapped or uprooted. Most roads are blocked, cutting off residential areas. Power is lost for months. Much of the area is uninhabitable for weeks.
5 (major)	252 or higher (catastrophic)	Many buildings are destroyed. Residential areas are cut off by fallen trees and power poles. Most of the area is uninhabitable for weeks or months.

Table 9.9 The Saffir-Simpson classification of the magnitude of tropical cyclones

High winds

The **Saffir-Simpson scale** (revised 2012) indicates the potential damage to structures by sustained wind speeds in tropical storms of cyclone strength.

The **Dvorak technique** has also been developed to estimate cyclone intensity on a scale from 1 (the least) to 8, based on satellite images of patterns in the weather systems, in particular the difference between the temperature within the eye and the coldness of the surrounding thunderstorm clouds. The greater it is, the stronger the tropical cyclone.

Storm surges and coastal flooding

Storm surges, abnormal rises of seawater, are secondary hazards of tropical cyclones. The strong winds drive the surge, which rises in shallow water and pushes inland, causing flooding. The highest part of the surge is where the strongest winds are. The lower the atmospheric pressure, the higher the surge because air rises in low pressure systems, taking weight off the sea surface, allowing it to rise. The surge will be especially high when:

- the storm has strong onshore winds
- it approaches the coast at right angles
- the coastline has bays and inlets to funnel the water
- the sea floor is gently sloping, with a wide continental shelf
- there are few obstructions, such as spits and islands, to slow the flow of water
- the storm coincides with high tide.

The greatest risk from cyclones is at the coast, because they lose power as they pass over land. The slower the cyclone moves, the greater the damage. Also, in the northern hemisphere the greatest risk is for the cities on the right of the eye's path because there the travel speed is added to the speed of the winds that are rotating anticlockwise.

Intense rainfall

Places crossed by the eye of a cyclone experience two bands of intense rainfall from the cumulonimbus clouds around the eye. This causes severe river flooding and mass movements, especially if the system is slow moving. River flooding is illustrated in the case study of Cyclone Yasi.

Mass movement

Super-Typhoon Durian, a category 5 storm, affected the Philippines in November 2006. Nearly all the 1200 deaths occurred when torrential rains saturated volcanic deposits on the slopes of Mayon volcano, causing mudflows that raced down the steep slopes onto the towns beneath. People had no time to escape as entire villages were buried under volcanic debris.

15. (a) Explain why Super-Typhoon Haiyan and Cyclone Yasi (Table 9.10) occurred at different times of the year.

(b) Compare and contrast the facts about Super-Typhoon Haiyan and Cyclone Yasi given in Table 9.10.

Case study: A comparison of intense tropical storms: Super-Typhoon Haiyan, Philippines (an LIC) and Cyclone Yasi, Australia (an HIC)

	Super-Typhoon Haiyan	Cyclone Yasi
Date	7 November 2013	3 February 2011
Width	600 km	1450 km
Category	both 5	
Dvorak intensity	8.1	6.5
Central atmospheric pressure	both 930 mb	
Maximum sustained wind speed	314 km/h	285 km/h
Highest storm surge	both 7 m	
Deaths	more than 6000	1
Homeless	nearly 2 million	a few thousand
Damage to structures	90 per cent of some towns destroyed	4000 buildings severely damaged
Total number of people affected (estimates)	11 million	400 000
Estimated cost	$US 2.9 billion	$US 3.6 billion

Table 9.10 A comparison between Super-Typhoon Haiyan and Cyclone Yasi

Case study: Super-Typhoon Haiyan (local name Yolanda), Philippines, 2013

A super-typhoon is a storm in the north-west Pacific with sustained wind speeds of 242 km/h or more.

Development

Haiyan grew from a tropical storm as it moved westwards, stirring up 15-metre-high waves. It reached its maximum intensity as it made landfall at Guiuan on the east coast of the central Philippines as the 25th typhoon of the season. It was so intense that it was off the Dvorak scale at 8.1.

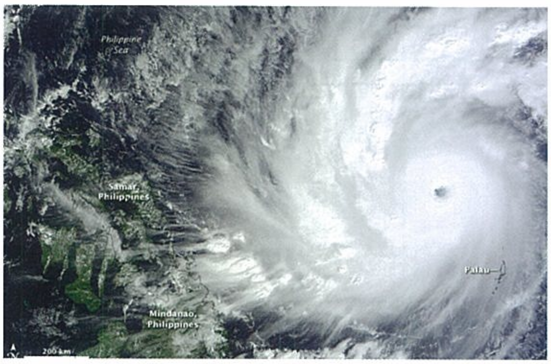


Fig. 9.43 Satellite image of Super-Typhoon Haiyan just before landfall in the Philippines. The eye is clearly visible, together with thick bands of eyewall cloud that produced powerful thunderstorms and very heavy rain. Most places had more than 140 mm in a day. The air is circulating anticlockwise in the northern hemisphere as it is being drawn in to the low pressure centre

Prediction, monitoring and perception of risk

Alerted by satellite images and the track of the typhoon, public storm warnings were issued and shelters opened but there were not enough for everyone and some of them were damaged beyond use by the storm. Many were very basic and not well stocked with essential supplies. Only half a million people were able to use them. The government advised evacuation but did not make it mandatory, so many stayed in their homes because they were afraid of looting. Many lives were saved by the major of Guiuan who constantly urged the residents to evacuate. The army, air force, navy and hospitals were on standby and disaster response teams were sent to areas expected to be affected.

Primary and secondary impacts on lives and property

Fortunately, the system moved so quickly across the country that rainfall totals did not produce the devastating floods and landslides that usually cause the most damage in Philippine typhoons. Although mudflows were less severe than usual, coastal areas were described as wastelands of mud and mudflows and debris slides destroyed many buildings in Guiuan.

Nearly all the damage was caused by the storm surge when Haiyan moved on to make landfall on the islands of Samar and Leyte. It was made more dangerous because Tacloban, a city on land less than 5 m above sea level on the island of Leyte, is on a bay where water was funnelled, causing a greater surge. An inhabitant interviewed on television commented, 'We survived the wind, but could not survive the water', and described it as 'like a tsunami'. The wall of water was over 7 m high and caused almost total devastation, especially in the shanty areas. The first floor of Tacloban City Convention Centre was submerged, drowning many evacuees being housed there. About 90 per cent of the buildings with wooden walls in the poorer parts of Tacloban were destroyed. Even well-built concrete structures had damaged roofs and windows and some were highly damaged. Many people drowned in the streets and many others were injured, as roads became rivers. The floods also swept away bridges and deposited large ships on top of the devastation.

Few buildings in the worst-hit rural areas were left standing. Fallen trees, roofs and tossed-up cars blocked roads. Power lines were destroyed, plunging the area into darkness; four provinces, including Leyte, had no power. Rotting corpses contaminated water supplies and spread disease. Survivors were without shelter, food, water, sanitation and fuel.

As the powerful winds had ripped down telephone lines, the inhabitants were unable to contact the outside world. Satellite images were invaluable for determining which areas were in most urgent need of assistance, as an archipelago over 7000 islands needed checking. Providing aid to them presented massive problems.

Supplies stockpiled for emergency use had been decimated a month before the typhoon when a 7.2 earthquake struck the island of Bohol; where about 5000 people were still living in tents.

After days without relief, desperate people looted for food and water to survive. Tacloban airport had been badly damaged by the storm surge and had lost its electricity supply, so only 20 daylight flights a day could bring in relief supplies and evacuate those in greatest need. Distributing aid was difficult and slow also because of blocked roads. The danger of attack from people desperate to intercept aid supplies caused aid agencies to delay going in until security was improved. Some islands are normally accessible only by ship and plane and planes could not land until runways were cleared of debris. Aid finally reached Tacloban seven days after the cyclone but it was nine days before food was available for distribution. People in the devastated and remote village of Guiuan waited longer. The disaster relief system failed because of a breakdown in power and communications.

Long-term effects

Mangrove forests were replanted along the coast, replacing those destroyed or previously felled because they protect against storm surges and strong winds.

The scale of the disaster was greater because Tacloban's population had trebled in recent years, despite the east coast being known to be the most hazardous for typhoon damage. Afterwards, many inhabitants of Tacloban and Leyte moved to less affected areas. About 20 000 went to Manila and the city of Catbalogan's population doubled because of the influx of refugees. Agriculture, the mainstay of the economy, was badly affected and temporarily slowed the growth of the economy.

Case study: Cyclone Yasi, Australia 2011

Prediction and monitoring

Cyclone Yasi, the fourth cyclone of the 2011 season to hit Australia, began as a tropical low pressure system near Fiji. It grew in intensity as it moved west before turning west-south-west over the warm South Pacific Ocean. It was expected to make landfall somewhere in the state of Queensland along a 300 km stretch of coast that included the cities of Cairns and Townsville, but people as far south as Brisbane were told to be prepared for dangerous flash floods. Heavy summer rain caused by La Niña conditions had fallen for the previous three months, resulting in damaged buildings and 35 deaths in river floods in the Brisbane area. More rain on already-saturated ground was likely to be disastrous. Only three days before Cyclone Yasi's landfall, Cyclone Anthony had uprooted trees and damaged power lines in Queensland.

16. Compare and contrast the cloud patterns in Figs 9.43 and 9.44 and suggest reasons for similarities and differences.

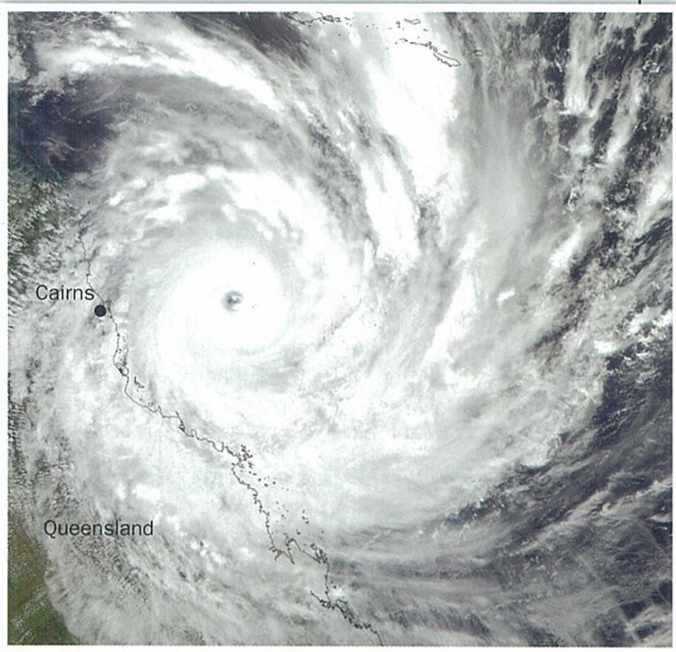


Fig. 9.44 Satellite image showing the enormous size of Cyclone Yasi, which measured 1450 km wide and 19 200 m from ground to cloud top

Perception of risk

- Rigorous building standards had been enforced after a cyclone in Darwin in 1974 killed 74 people.
- The public were informed through the media to prepare for an event worse than anything previously experienced. Storm surge forecasts were given for a high tide situation.
- People in low-lying areas along the coast from Cairns to Townsville were told to evacuate and 29 000 did, including hospital patients moved by the military.
- Schools, universities, airports and ports were closed.

Primary impacts on lives and property

Yasi hit as a category 5 cyclone, destroying the anemometer, radar equipment and communications with the outside world on Willis Island. It moved on to the mainland, affecting 540 km of coast with 400 000 inhabitants, but missed the main cities. It made landfall at midnight at the small settlements of Mission Beach, Cardwell and Tully. Hundreds of homes and businesses, including strongly-built brick buildings, were badly damaged. Strong winds and a 7-metre-high storm surge caused damage up to 300 km inland. Roofs were ripped off and Tully High School was destroyed. At least 226 000 properties were left without power and the water supply system in Townsville failed. Expensive boats and yachts were destroyed. However, because people had followed advice to evacuate, there were few injuries and only one death.

The impact was less severe than it could have been because:

- Yasi turned south just before landfall into a region with low population density, missing Cairns.
- It moved at an unusually rapid speed (35 km/h), which limited rainfall amounts and the length of time structures were battered by the winds.
- As the storm surge did not coincide with high tide, it was 2 m lower than it would have been.

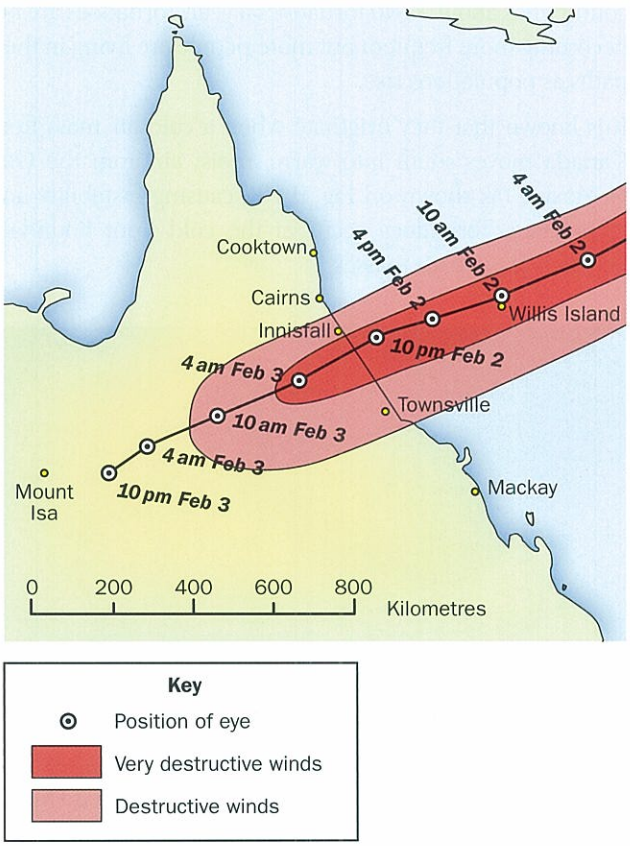


Fig. 9.45 The enormous area affected along the track of Cyclone Yasi

Yasi maintained cyclone strength until more than 700 km from the coast, where it was downgraded to a tropical storm near Mt Isa. It was the costliest Australian cyclone as banana and sugar cane fields were extensively damaged; the state's main exports were lost, including 75 per cent of Australia's banana crop. Estimates put the losses to agriculture, mining and local government at US$ 2 billion, with a further US$ 1 billion cost to the tourist industry.

Record-breaking daily rainfall totals were received over a wide area of Queensland. River floods were extensive and many roads were cut. The highest totals fell from the cloud band south of the eye. Mission Beach recorded the highest daily total of 471 mm and most places had more than 200 mm.

There was little need for urgent relief because of the very good planning by the authorities and the sensible response of residents to warnings and advice. The main problem was to deliver emergency supplies to the many communities isolated by the flooding.

Power supplies were restored quickly and the military helped with the clear-up operation. Nearly 3000 km of road had to be repaired and the railway rebuilt.

Secondary impacts resulting from the primary impacts

- As parks and forests were extensively damaged, the cassowary, an endangered bird species, lost much of its rainforest habitat and food sources.
- Strict building regulations were put in place to make new coastal properties storm surge proof.
- Heavy rain damaged the Great Barrier Reef off the coast, as polluted run-off caused a population explosion of Crown of Thorns starfish, which eat coral polyps.

The people of Queensland were remarkably resilient. Most of the infrastructure was repaired quickly. One year after Cyclone Yasi, farmers were growing bananas and sugar cane again. Bank loans and insurance pay-outs enabled most people to rebuild their homes and re-start their businesses.

In comparison, the resilience of the US city of New Orleans after Hurricane Katrina was considerably less than that of Queensland, partly because many people were too poor to have insurance. A year after the disaster the population of New Orleans was only half what it was before.

Tornadoes

A tornado is a violent, rapidly rotating and fast moving, narrow, funnel-shaped column of cloud that extends from the base of a cumulonimbus cloud to the ground. The very strong rotating wind makes it the most violent type of storm on Earth. Much stronger winds can occur than in cyclones, reaching speeds of 500 km/h. Tornadoes have extremely low pressure and usually last only a few minutes. The pressure falls rapidly as the tornado approaches, is very low in the centre and rises very quickly afterwards, as in a tropical cyclone, but there are differences in scale between these two weather systems. Average central pressure is not known with confidence (because the tornado usually destroys recording instruments) but 850 mb, lower than in a cyclone, is the lowest-recorded central pressure and it was measured dropping extremely rapidly by 100 mb to 850 mb in a few minutes. The majority of tornadoes are less than 600 m in diameter and have a path width of less than 50 m. Although most touch the ground for less than 4 km, the record contact was for just over 350 km.

Most tornadoes become darkened by the debris they pick up. The most dangerous tornadoes occur when the approaching hazard is not noticed because the funnel shaped cloud is hidden by rain or dust.

As well as varying in size, they also vary in shape. **Stovepipe tornadoes** are narrow and cylindrical, whereas very wide ones are **wedge tornadoes** (Fig. 9.50).

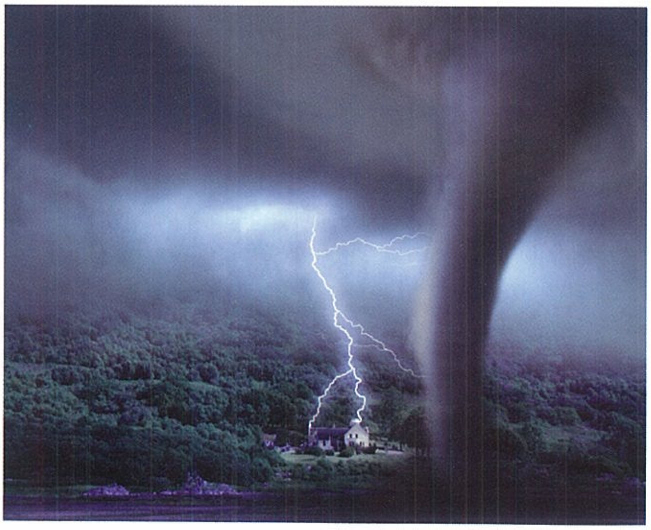


Fig. 9.46 A stovepipe tornado and lightning in Scotland

Although tornadoes are too small to be affected by Coriolis force, most do rotate anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. The rotation is believed to be started by wind shear. Although they generally move in the USA from south-west to north-east, they can take strange, unpredictable paths and can be almost stationary or race across the ground at 80 km/h. Lightning, hail or very heavy rain can accompany them.

Fig. 9.47 A stovepipe tornado in Oklahoma with a dust cloud surrounding its rotating cloud base

Processes leading to the formation of tornadoes

Tornadoes are not fully understood and are being intensively studied in the USA in the hope of being able to give warning of their approach as long as possible beforehand, as the country has about 1200 tornadoes a year. Tornadoes are not becoming more frequent but more people are living in their paths as populations rise.

It is known that they originate when a cold air mass from Canada moves south into warm, moist air from the Gulf of Mexico (as shown on Fig. 9.48), causing instability and turbulence. Tornadoes occur at the cold front boundary between the two air masses.

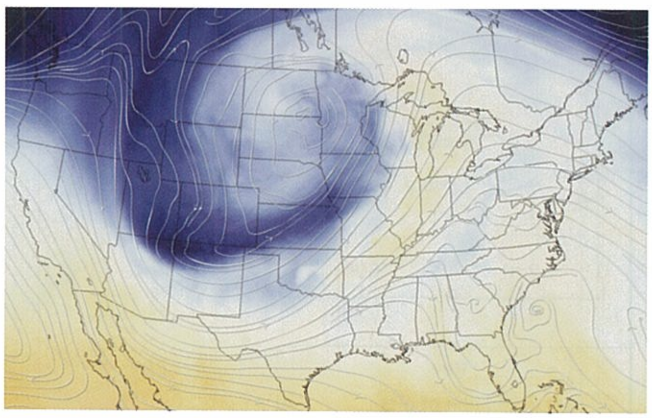


Fig. 9.48 NOAA image of the cold (blue) and warm (orange) air masses at high altitude that caused tornadoes on 20 May 2013, together with lines showing the high altitude wind pattern

It is also known that tornadoes form from rotating **supercell thunderstorms** and always come from a cumulonimbus cloud. However, only 20 per cent of supercell thunderstorms develop tornadoes. They form in the warm, moist air, usually with a temperature in excess of 18 °C. Supercell thunderstorms are extremely violent and have large updrafts extending to the top of the cloud. These

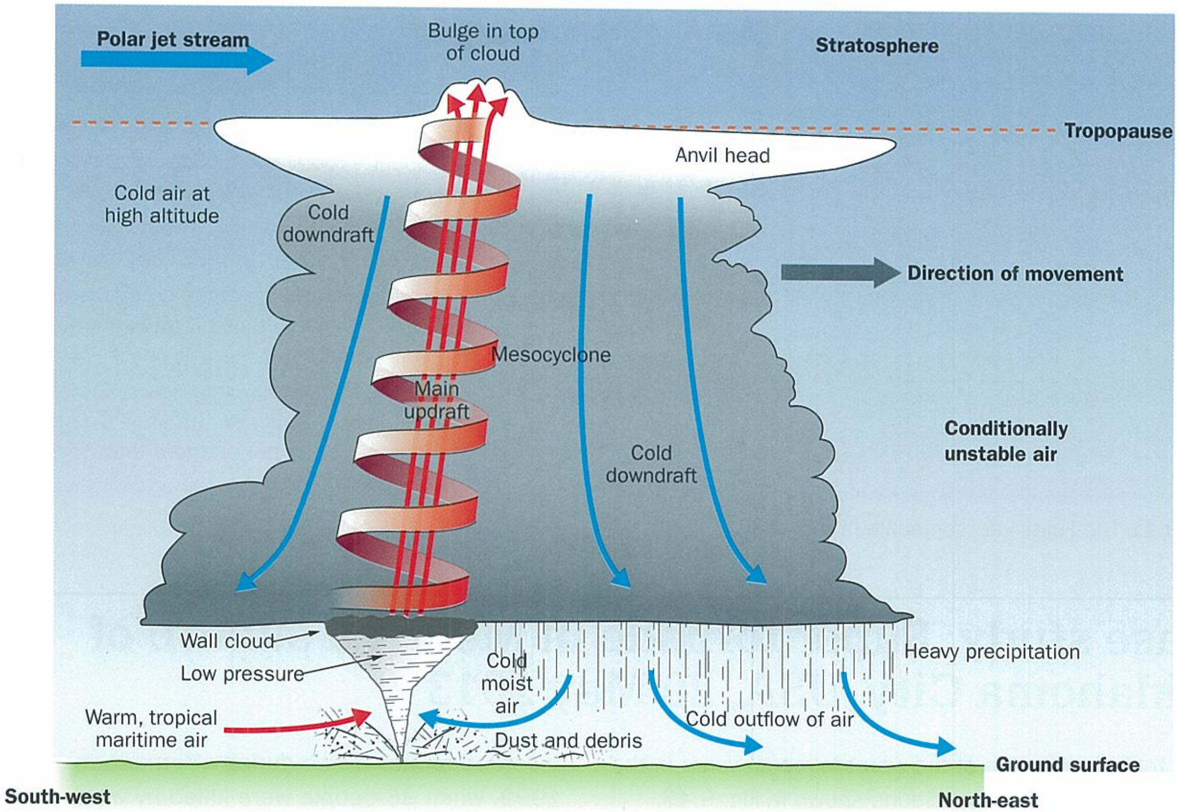


Fig. 9.49 The formation of a tornado from a supercell thunderstorm

rotating up-currents, known as **mesocyclones,** can be up to 16 km in diameter. About half of them become tornadoes by extending downwards, spiralling to reach ground level, narrowing as they do so.

The rotation may be started by a wind shear - winds blowing in different directions or at different speeds, such as when a strong horizontal upper air wind meets a violent updraft. This would cause a horizontal rotation, which is then forced to rise with the strong updraft.

The first stage in the life cycle of a tornado occurs when heavy rainfall in the cumulonimbus cloud drags a column of rapidly descending air down with it, which, in turn, drags the mesocyclone towards the ground.

As the mesocyclone lowers, it pulls in warm, moist air from kilometres around, as well as very humid air from the rainy area at the cloud base. The moisture in this quickly condenses to form a rotating **wall cloud,** an isolated cloud that projects below the rest in the rain-free part of the storm. The increasing outflow of cold air concentrates the base of the mesocyclone into an increasingly smaller area from which to draw its air intake. The updraft grows in intensity, creating a low pressure near the surface. This pulls the mesocyclone down as a funnel cloud. When the downdraft reaches the ground 10 to 20 minutes after the wall cloud forms, it creates a gust that causes severe damage over a considerable distance. Soon after, the funnel cloud itself becomes damaging and dust and debris get drawn into it.

The tornado grows in intensity while it is supplied with warm, moist air, which expands in the low pressure and cools, releasing latent heat when the water vapour condenses. When the funnel cloud has grown to its widest extent and is vertical, the tornado is in its most damaging mature stage, often with very destructive hailstones, up to the size of grapefruit.

Eventually, cold air from the downdraft spreads at the ground surface and cuts off the supply of moist, warm air that was fuelling the tornado. It then rapidly weakens and the funnel becomes wavy and rope-like, before disappearing.

A classification of tornadoes

Tornadoes are measured on the **Fujita-Pearson scale** (Table 9.11), which is really three independent scales measuring wind speed, path length (PL) and path width (PW).

The frequency with which tornadoes occur decreases down the scale.

Tornado hazards

The main hazard is being hit by flying debris or massive hailstones. Other dangers are being lifted up and blown through the air until hitting an object or being crushed, either by falling trees or by collapsing parts of buildings. Broken power lines are a secondary hazard.

Scale	Force (km/h)	Category	PL (km)	PW (m)	Damage
F0	0–116	Weak	less than1.6	less than 16	light – damage to chimneys, sign boards, broken tree branches and shallow-rooted trees
F1	117–180	Weak	1.6–5	16–50	moderate – damage to roofs and mobile homes
F2	181–253	Strong	5.1–15.9	51–160	significant – roofs and mobile homes destroyed, large trees uprooted, light objects blown into the air
F3	254–332	Strong	16–50	161–508	severe – roofs and walls of well-constructed homes damaged, trains overturned, cars thrown in the air
F4	333–418	Violent	51–159	509–1448	devastating – well-constructed houses destroyed and blown some distance if foundations weak, large missiles in the air
F5	419–512	Violent	160–507	1449–4989	incredible – strong houses moved some distance, steel-reinforced concrete structures damaged badly, cars flung through the air more than 100 m, bark stripped from trees

Table 9.11 The Fujita-Pearson scale of tornadoes

Case study: Super tornado in Moore, a suburb of Oklahoma City, USA, 20 May 2013

This tornado was one of the worst in recent years in the USA. It formed in the conditions shown in Fig. 9.48.

Risk perception

The Oklahoma Department of Emergency Management advises inhabitants to:

- keep informed about the weather by listening to local weather forecasts and to have a battery-operated NOAA Weather Radio, which has a warning alarm feature
- sign up for free cell phone (mobile phone) or email alerts
- plan well ahead, knowing what to do to keep safe
- get inside a strong building when a tornado threatens. Go to its lowest floor: preferably a basement. Keep as far away from windows, doors and outside walls as possible
- cover up to protect from flying or falling debris. If possible, wear a hard hat
- avoid being in a mobile home or vehicle.

Many homes have reinforced underground storm shelters but these are too expensive for the poorer people in the community. Schools have weather safety shows and annual drills.

Not everybody takes notice of the warnings because about 75 per cent of them prove to be false and people do not like wasting time. However, it is likely that most people in Moore would have taken the warning seriously because the fastest wind ever recorded on Earth was during a tornado there in 1999, when 36 people were killed by winds that reached 486 km/h. The suburb's population was better prepared as a result of their past experience.

Primary and secondary impacts on lives and property of the super tornado on May 20 2013

The F5 'monster' touched down outside Oklahoma City 16 minutes after the warning was issued. The mayor estimated that the warning saved about 1000 lives. After touching down and tossing horses into the air, it headed east-north-east into Moore, where it did enormous damage.

Fig. 9.50 The wedge tornado that devastated Moore in 2013

Most tornadoes are very localised, but this one was an unusually wide wedge type so, instead of destroying a street, it flattened whole housing estates, reducing two- and three-storey buildings to piles of sticks. It also destroyed two primary schools. The first one was so damaged that it is incredible no one sheltering there died. The tornado had strengthened to 320 km/h when it reached the second school, which had no shelter. It caused the greatest loss of life when the roof tore off and a wall collapsed, destroying the hall, the safest area, where the children were sheltering. Moore hospital, a cinema and bowling alley were also damaged and fires broke out.

Cars were tossed in the air and facades stripped from buildings. Power lines left lying across roads and pavements created obstacles to movement and danger from power outages.

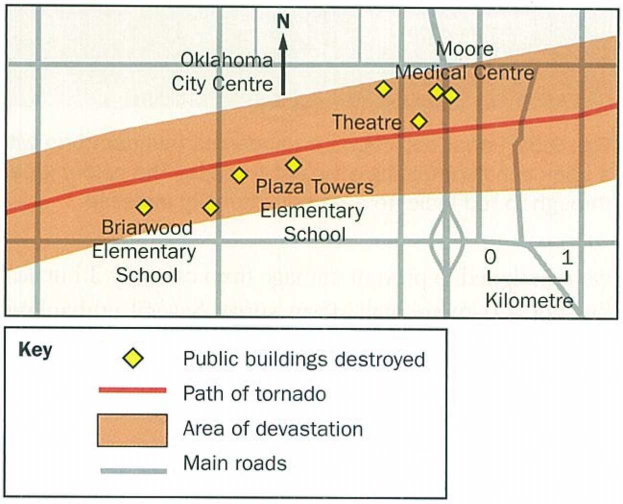


Fig. 9.51 The path of the tornado at Moore, 20 May 2013

The tornado was on the ground for 45 minutes, leaving a path of devastation 27 km long and 2.4 km wide. There were 24 deaths (including seven at the primary school), 237 injuries, 2500 homes demolished or damaged and a total of 10 000 people affected. Gas and water supplies were cut.

A state of emergency was declared and disaster assistance agreed by the US government. Emergency workers from nearby states searched with sniffer dogs for survivors and cleared wreckage that lay over underground shelters. They were hindered by the loss of telephone communications, as lines had been brought down and cell phone networks were jammed as so many people were trying to use them. Power was restored to the hospital quickly. Doctors and nurses were brought in and volunteers with aid organisations served food and helped people search for belongings.

The Moore tornado was not accompanied by a large hailstorm but the day before Moore was devastated, a tornado with hailstones up to 10.8 cm in diameter had struck Shawnee, another suburb of Oklahoma City and completely destroyed a mobile home park.

17. Suggest why tornadoes in Bangladesh kill an average of nearly 180 people a year, more than anywhere else in the world.

Prediction and monitoring of large and small-scale atmospheric disturbances and perception of risk: how the USA prepares for hurricanes and tornadoes

Hurricane prediction and monitoring

Meteorologists in the national Hurricane Centre in Florida track storms on satellite images to provide warning in time for people in the USA and surrounding countries to put strong covers over their windows and evacuate. Satellites have made weather forecasting much more accurate. Meteorologists fly in planes with their instruments across the eyewalls and eye of hurricanes to measure their strength. However, predictions of where the storm will hit are not always successful because tropical storms can suddenly change course and their speeds of movement can vary. Exactly where they will make landfall is not known until very near the time it actually happens. This causes a problem for the state governor and department responsible for giving the order to evacuate.

The Federal Emergency Management Agency makes sure places are prepared for disasters. Practice drills are held regularly. The Hurricane Centre uses various methods to educate people of the dangers they face and what to do if they are caught in a hurricane.

Tornado prediction and monitoring

Prediction of tornadoes is improving all the time. When satellite imagery shows the situation is right for them to form (Fig. 9.48), NOAA sends out a Tornado Watch announcement to the media and arranges for a satellite to send back imagery of the area every five minutes, instead of the normal 30 minutes. Meanwhile, another satellite over western USA acquires imagery at one-minute intervals. Meteorologists also monitor Doppler radar for supercell thunderstorm clouds that have a hook echo at their rears, as these are known to be associated with tornadoes. The large rotating updraft (mesocyclone) from which a tornado may form also helps meteorologists to spot them with more time to warn before it strikes a community. Radar can even detect debris, allowing the location of a tornado to be detected at night or when it is raining. People trained to be tornado spotters then go out to visually confirm the tornado, reporting back to the National Weather Service. The local Weather Service Forecast Office then issues a Tornado Warning and urges people to reach safe shelter.

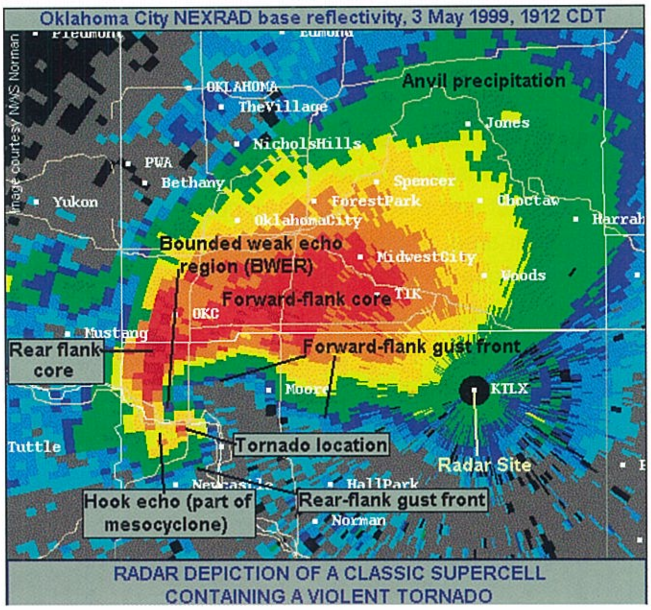


Fig. 9.52 Radar depiction of a supercell thunderstorm with a hook echo containing a violent tornado. The colour green through to red indicate a rainfall intensity increase

Perception of risk

People who have not experienced the hazard are not usually willing to take the necessary action to avoid it. In 1992 when Hurricane Andrew threatened southern Florida, the authorities decided to evacuate people from coastal areas likely to be affected. The decision to do so was difficult because the economy is harmed by stopping normal life, so the authorities who make the decision to evacuate are strongly criticised if a disaster does not occur. The hurricane proved devastating, with 80 000 homes destroyed and 15 deaths amongst citizens who refused to evacuate because they had never known a hurricane affect as far inland as Hurricane Andrew reached.

Inappropriate risk perception was also a factor in the Hurricane Katrina disaster. There were both physical and economic reasons why Hurricane Katrina killed more than 1800 people in the city of New Orleans, in the marshes of the Mississippi delta, USA. Built on soft, easily-eroded sediment, much of the city was below sea level, some more than three metres below, with the seawater kept out by concrete embankments. Economic reasons also contributed to the disaster in New Orleans because it was not thought to be cost-effective to spend a lot on protection against events considered unlikely to happen in a long time period. Therefore, the embankments and floodwalls were designed to prevent damage from category 3 hurricanes but not a 6-metre-high storm surge. Several embankments collapsed and 80 per cent of the city was flooded by as much as three metres. There was little wind damage because buildings had been built to withstand hurricane winds.

Where risk perception leads to protective measures against hurricanes being taken, much depends on the effectiveness of those used against flooding (described in Chapters 1 and 8). People are also deterred from living in vulnerable areas, such as floodplains, by increasing the cost of their insurance.

The integration of hazard prevention measures into the planning of new developments may make it possible to avoid flood damage altogether. Land-use zoning is used to reduce the cost and inconvenience of flooding; floodplains are used for playing fields, pasture and nature reserves, whereas buildings are placed at higher levels.

Case study: The Philippines: a multi-hazard country

The Philippine islands have many typhoons because they are located to the west of a huge area of warm water in the Pacific Ocean. As the case study of super-typhoon Haiyan showed, they experience problems in sustainably managing an environment made hazardous by flooding and typhoons but have some success in reducing the danger from volcanic eruptions.

Problems of sustainable management

As the Philippines is a poor country and a multi-hazard location, it has to balance what to spend on disaster-resistant infrastructure with which basic services to provide. Consequently, many schools and hospitals are not built to withstand hazards and many sustainable management methods are too expensive to employ.

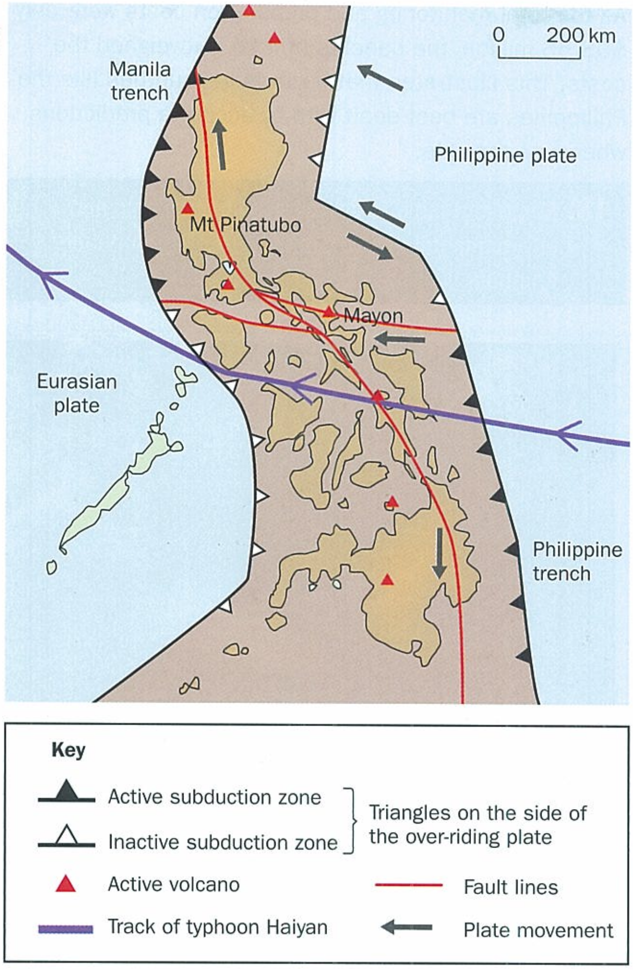


Fig. 9.53 Some of the hazards in the Philippines. The main plates are crushing small plates between them. The map does not show the many areas prone to landslides and floods or the tracks of other typhoons that cross the country anywhere from east to west

The country's population has risen from 19 million in 1950 to almost 100 million, so increased deaths are inevitable as an increasing number of people live in vulnerable locations.

Some of the severity of the frequent flooding has been blamed on inadequate drainage systems, but deforestation has been more damaging. The original cover of tropical rainforest, the barrier to landslides and mudflows, has been almost entirely cleared for export income. After disastrous flooding, landslides and typhoon deaths in 2011, the government, like several governments before, banned any new cutting of natural forests – but large amounts of illegal logging still occurs.

The need to use funds for restoration and recovery after each of the 20 or more typhoons that afflict the country each year continues the cycle of poverty. There are no resources left to put in place measures to protect against the next disaster. The country lacks funds to construct many expensive canalised channels which would move flood waters away quickly.

Whereas many emergency shelters, well-stocked with food and water, are set up within easy reach of communities in HICs, they are few and more spread out in poorer countries like the Philippines. Few people can afford insurance to cover possible losses.

The country also does not have the same amount of technology or technological knowledge available as a rich country.

The eruption of Mt Pinatubo, Philippines, June 1991

Mt Pinatubo is a stratovolcano on the island of Luzon where the South China Sea plate, part of the Eurasian plate, subducts eastwards under the Philippine Sea plate.

Luzon is a very densely populated island, with one million people living within 30 km of the volcano. It had not erupted in 500 years, so it is remarkable that the second biggest eruption of the 20th century caused relatively small loss of life.

The first sign of activity was in April 1991 when many small earthquakes accompanied the emission of thousands of tonnes of noxious sulphur dioxide gas. On 15 June there was a cataclysmic explosion of 5 cubic km of material. The ash cloud rose 35 km into the air and the typhoon affecting the area at the time blew ash in all directions, covering a very wide area. Pyroclastic flows of hot gas and ash moved at high speed down the slopes and giant lahars swept rapidly down valleys onto the lowlands as intense typhoon rains mixed with ash deposits.

Impacts on lives and property

Only 847 people were killed, 300 by roofs collapsing under the weight of wet ash accumulations, 100 by lahars and the rest from disease due to poor sanitation in the evacuation centres. Over 1 million people lost their homes and the cost of the eruption was about $US 700 million.

Droplets of sulphuric acid formed in the ash cloud and caused $US 100 million damage to flying aircraft. Manila airport closed for a time.

As annual rainfalls of up to 4000 mm occur on the volcano, lahars removed about half the deposits on the slopes during the next four rainy seasons. They caused more destruction than the eruption by burying towns and the lowlands under 3 cubic km of material in four years, making 200 000 people homeless, destroying the 1991 harvest, roads and bridges. The buried farmland was unusable for many years.

Reasons for the unexpectedly low loss of life

Prediction, monitoring and risk perception successfully kept the death toll small.

- In March 1991 scientists installed seismometers, tilt meters and other monitoring equipment on the volcano. They drew hazard maps and geologists studied the area and discovered that lahars had been a hazard in the past.
- The population was informed that a serious threat existed. Daily bulletins about the alert level were issued on TV, radio and in newspapers.
- On April 7, people living within 10 km of the volcano were evacuated.
- On June 7, scientists warned that a major eruption was imminent. People were evacuated from the zone within 10–20 km of the volcano.
- On June 13, people were evacuated from the 20–40 km zone.
- 200 000 people were evacuated to the Velodrome in Quezon City, one of the evacuee camps provided by the government.
- Soon after the eruption, a new lahar hazard map was produced and a system to monitor and warn of future lahars was established.

Monitoring and preparation before the eruption was thought to have saved at least 5000 lives. Large potential financial losses were prevented by moving aircraft and other expensive equipment to safe areas.

As the total monitoring and preparation costs were only $US 56 million, the benefits of it far outweighed the costs. This illustrates that hazards in countries like the Philippines are best dealt with by accurate predictions whenever possible.

18. Compile a table to list the social, economic and environmental impacts of the1991 Mt Pinatubo eruption.

Fig. 9.54 The ash cloud emitted during the Plinian eruption of Mt Pinatubo in 1991

The human factor in vulnerability to hazards

Vulnerability and the number of hazardous events has increased and can be predicted to continue to rise because population growth is forcing people to live in places where they are more vulnerable, such as on steep hillsides in squatter settlements on the edge of cities in LICs. The most vulnerable are the poorest in society, who have little opportunity to do otherwise and who may be relatively poorly educated and completely unaware that they are living in a potentially dangerous location. The rich can afford to move quickly out of danger and can afford to regain a normal life more rapidly after a hazard event. Also, the very young and elderly are weaker and less able to migrate or withstand the effects of a hazard on their health.

Vulnerability also depends on:

→ The degree of technical ability to monitor the hazard and to take preventative or protective actions to minimise it. **Prevention** is achieved by taking action to avoid the adverse impact of the hazard whereas **mitigation** attempts to limit the adverse impacts.

→ The degree of education and practising of emergency drills gives awareness of how to minimise potential danger.

→ Individuals are less likely to be well-prepared than communities with organisations which take on responsibilities on behalf of all.

→ Different economies have different types of vulnerability; hazards in HICs have relatively small loss of life but high economic costs, whereas in LICs the economic costs are low but the death toll is high.

19. Describe the different types of economic losses incurred in HICs as a result of a hazardous event.

Human responses to hazards are possible when risk is perceived

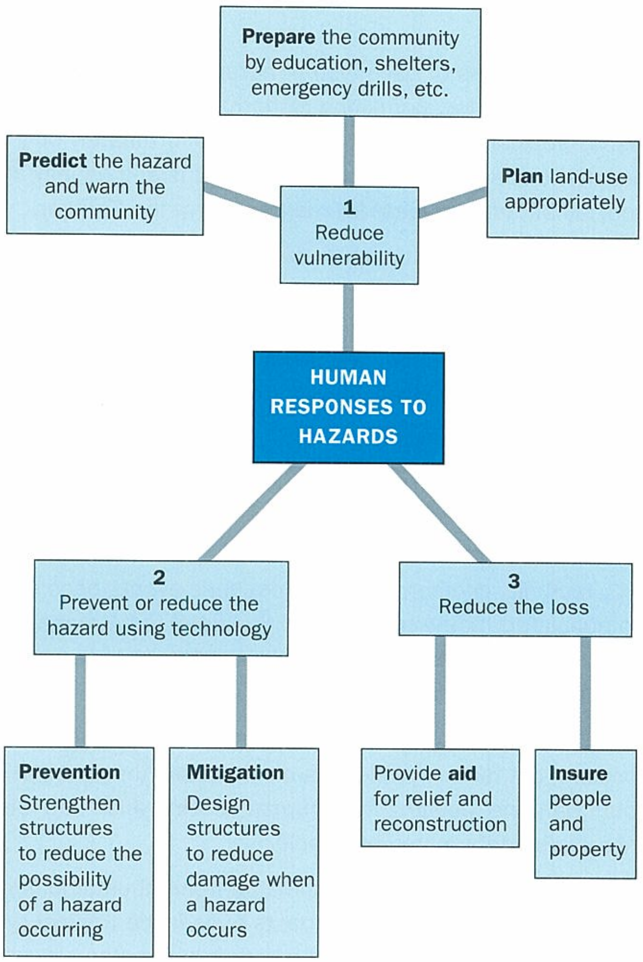


Fig. 9.55 Types of human response to hazards

20. Explain, with reasons, which of these responses to hazards are likely to be most useful in LICs.

Risk perception leads to improved hazard management

Sustainable development is possible in high-risk areas if the public and private sectors act to mitigate or prevent future hazardous events. Risk assessments help decisions about whether or not redevelopment should take place.

- Construction measures and land-use zoning save lives and prevent damage.
- Hazard mitigation is improving. Loss of life during hurricanes has been reduced in the Caribbean by early warning systems. Flood damage in some HICs is reduced by prohibiting building on floodplains, enforced by insurance conditions.
- Hazard mitigation is now seen to be cost-effective.
- Hazard management is most effective when all sectors in the area are involved in integrated development planning.

A pronouncement by the UN in November 2015 suggested that the future is less optimistic. It stated that, worldwide, deaths from hazards caused by climate change have increased. It is true that 90% of deaths in the Philippine hazards since 1990 resulted from storms and associated floods and landslides, with only 8% from tectonic hazards, but it is taking a very simplistic view to claim these deaths are caused by climate change alone. The contributions of deforestation, which has left only 3% of the original protective forest cover and a population increase of nearly 40% since 1990 (from 62 million to 102 million in late 2015) have been ignored. At the same time, the President of the Philippines announced plans to build 23 new coal-fired power stations.

An equation of disaster risk, $R = (H \times V)/C$ maintains that hazard risk increases as people's vulnerability increases and their coping ability decreases. For the Philippines and other poorer economies this holds true, but the reasons are complex and partly economic.

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: this is seen in the different distributions of each type of hazard, ranging from the generally linear patterns of the tectonic hazards that results from their location along plate margins, to the more haphazard pattern of mass movements with a variety of causes. Tropical atmospheric disturbances fortunately only occur in certain well-defined locations. They form only in atmospheric space over warm tropical oceans and usually affect the east coast of continents in tropical and sub-tropical latitudes at least five degrees from the Equator.

Scale: none of the hazards occur on a global or continental scale, although tectonic hazards occur in belts that circle the world and ash clouds from major eruptions stream round the world in the atmosphere. Spatial scale is also demonstrated by atmospheric hazards in that the effects of tropical cyclones are felt over a much larger area than those of tornadoes which are extremely localised. The development of hazard warning maps uses present day indicators, but also evidence from a wide timescale, as clues to the occurrence of landslips and lahars in the past are invaluable for predicting their location in the future.

Place: places that are endangered by hazards have physical characteristics that make them vulnerable: plate boundaries for tectonic hazards, low lying coasts on estuaries for tsunamis and cyclones and steep slopes for mass movements.

Environment: localities affected by tectonic, geomorphic or atmospheric events become challenging hazardous environments when they are also populated. Some human activities need to be managed if they are to be sustainable. Large-scale deforestation has increased both river flooding and landslides while the removal of mangrove forests from some coastal areas has increased the vulnerability of people to tsunamis.

Interdependence: the links between physical and human processes are two way – physical processes result in hazards that affect human lives and processes, but human processes can intensify the physical processes. The danger from storm surges is increased by global warming resulting from human activity which has raised sea levels and the choice of low lying coasts for settlements is also determined by people.

Diversity: tectonic hazards affect a variety of different environments from mountainous destructive plate margins to the oceanic ridges of constructive plate margins, while tropical coasts experience tropical cyclones, but tornadoes strike temperate continental interiors. People and cultures affected by hazards are also diverse; some live in high income countries while others in low income economies have less ability to take adequate precautions. Responses of local people to the known hazard also vary between different economies and even cultures, as a few can have a fatalistic outlook.

Change: hazards are extremely dynamic, as they can dramatically alter landscapes and lives in a matter of seconds. The impact of earthquakes is instant, as are landslides and rock falls. Tornado systems move extremely quickly over the surface, often touching down and rising from the surface in a matter of seconds. Cyclones are slower but are nonetheless dynamic in the destruction they cause.

Exam-style questions

1

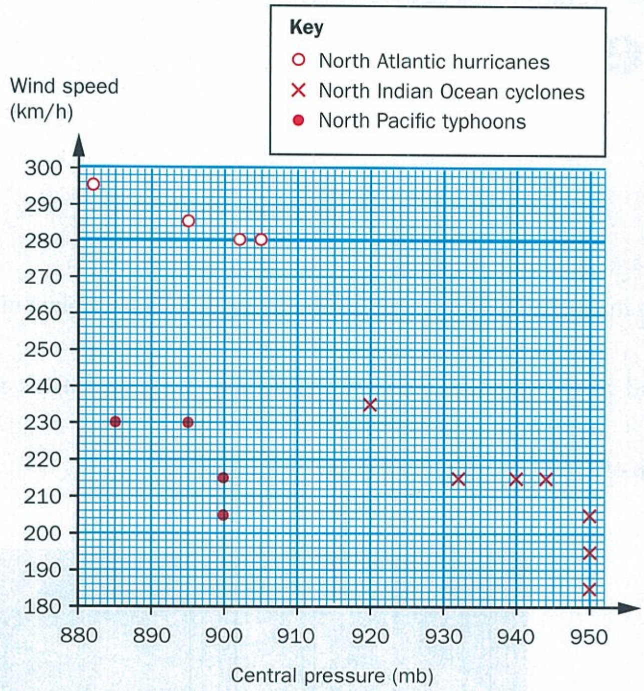


Fig. 9.56 Major tropical storms (cyclones) that have occurred in the northern hemisphere oceans since 2000

(a) Describe how the major cyclones that have occurred since 2000 in each of the North Atlantic, North Pacific and North Indian Oceans are different from those in the other two oceans. [4]

(b) Describe and explain any relationship between central pressure and wind speed for the tropical storms in the North Atlantic and North Indian Oceans. [6]

2 To what extent do you agree that hazards are made worse by human activity? Use examples to support your argument. [20]

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.

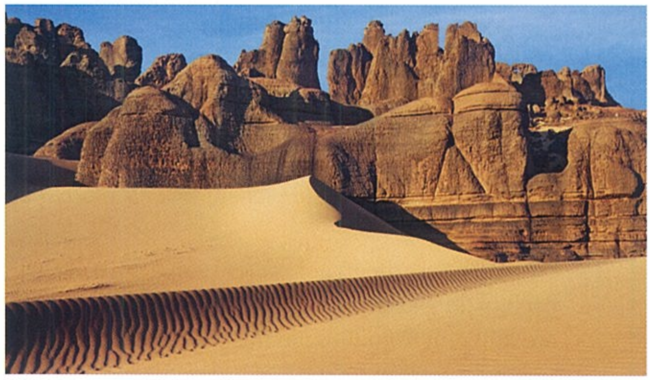


Fig. 10.1 A sand and rock desert in the Sahara, Algeria

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.

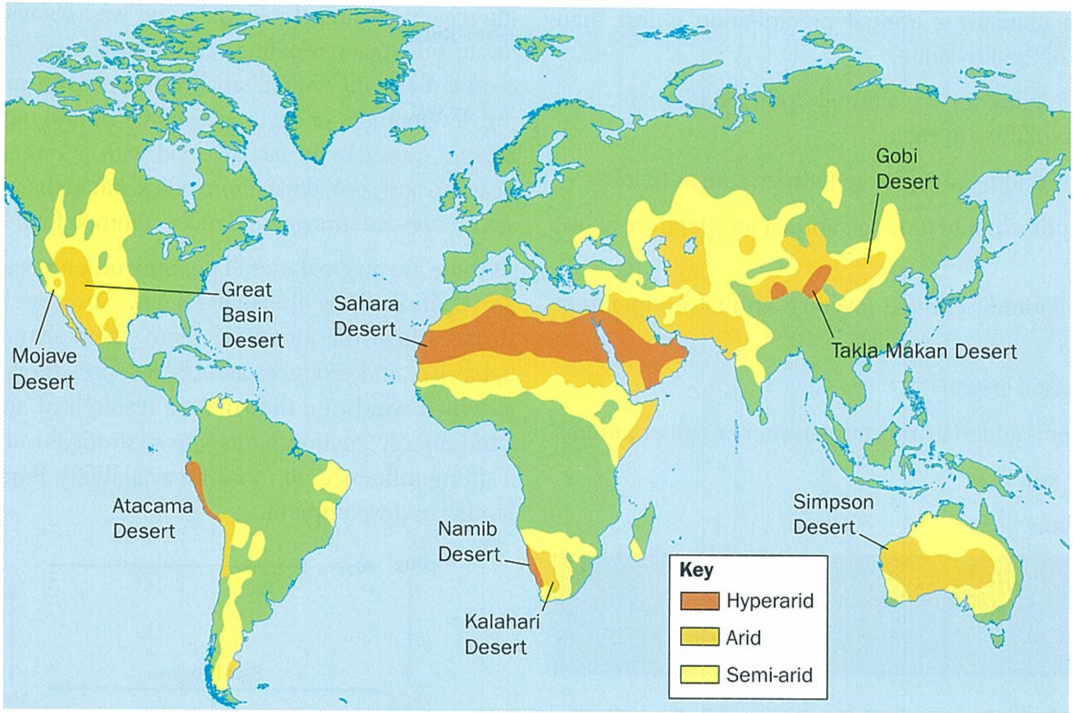


Fig. 10.2 The world distribution of hyperarid, arid and semi-arid areas

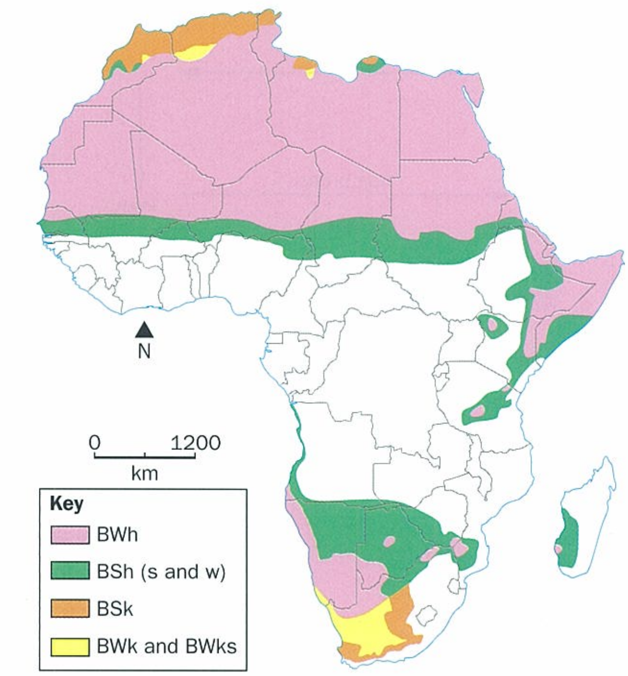


Fig. 10.3 A simplified map of arid climates in Africa using the Köppen classification

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.

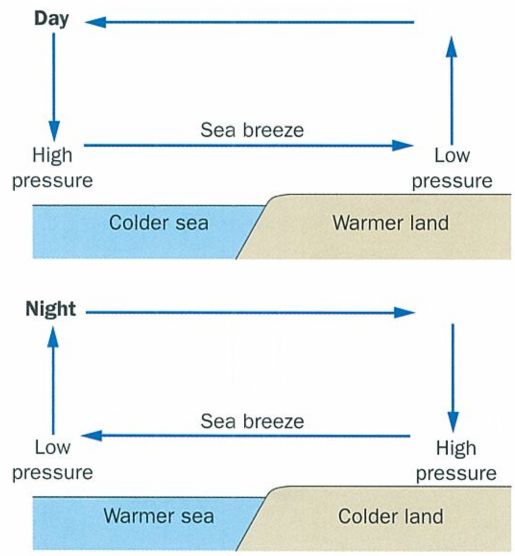


Fig. 10.4 The formation of land and sea breezes

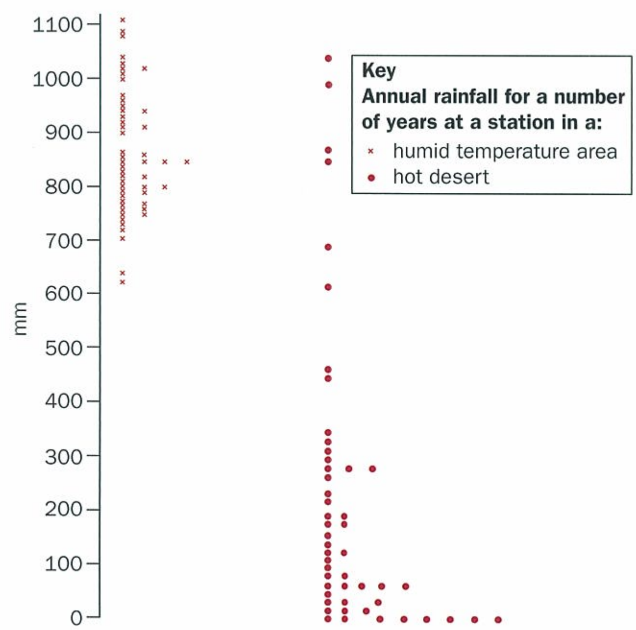


Fig. 10.5 Dispersion graphs showing the annual rainfall for a number of years at a station in a humid temperate area (crosses) and a station in a hot desert (circles)

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?

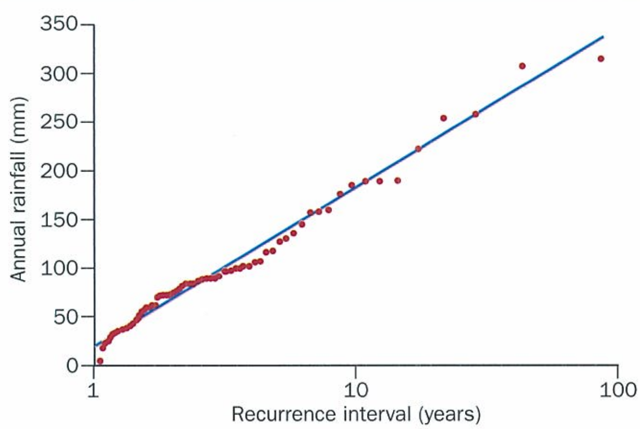


Fig. 10.6 The recurrence intervals of annual rainfall totals in a hot arid areas showing a lognormal distribution

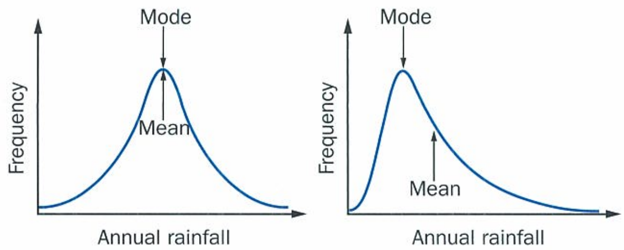


Fig. 10.7 Distribution curves for annual rainfall at two places, one showing a normal distribution and one showing a lognormal distribution

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

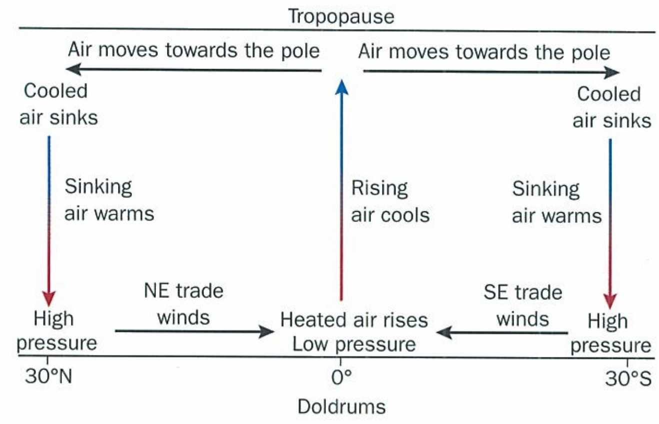


Fig. 10.8 The Hadley cells

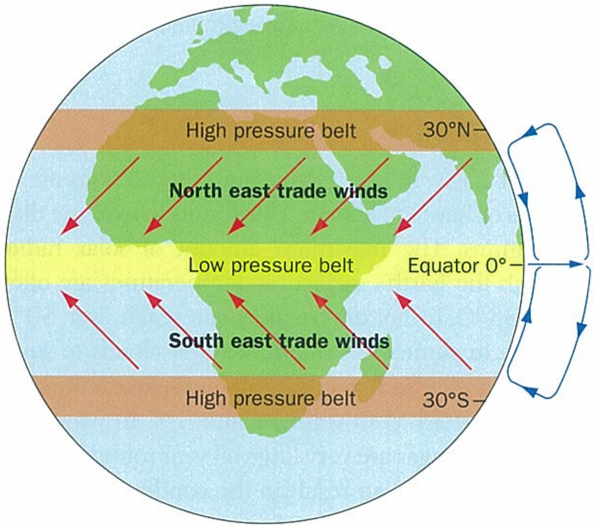


Fig. 10.9 The winds and pressure belts influencing the tropical desert climates

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.

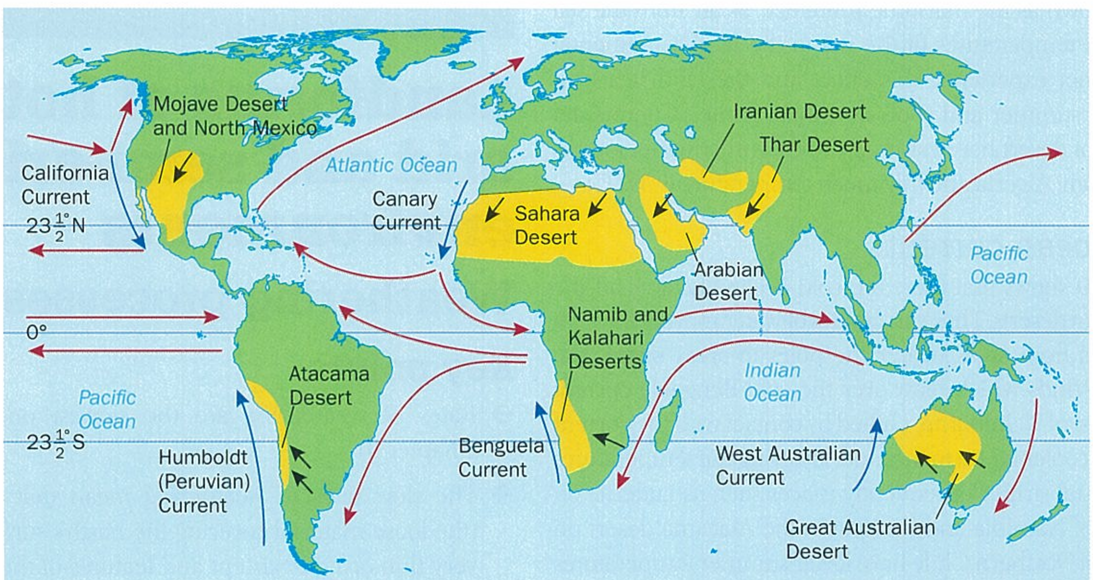


Fig. 10.10 The influence of ocean currents on hot arid and semi-arid climates

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

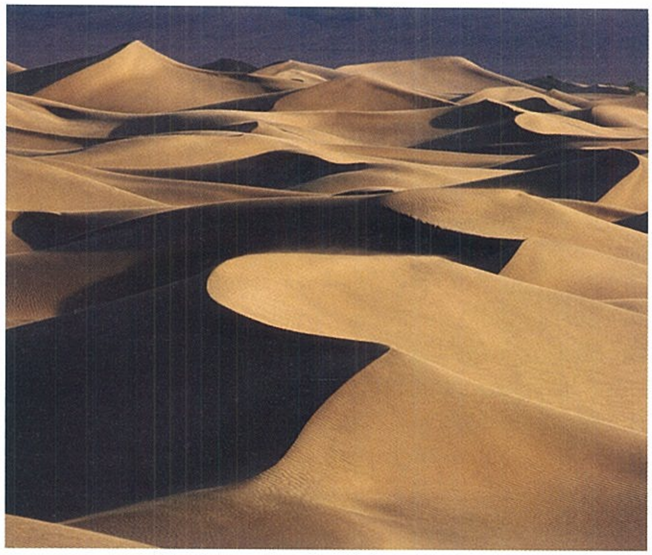


Fig. 10.13 A sandy desert, California, USA

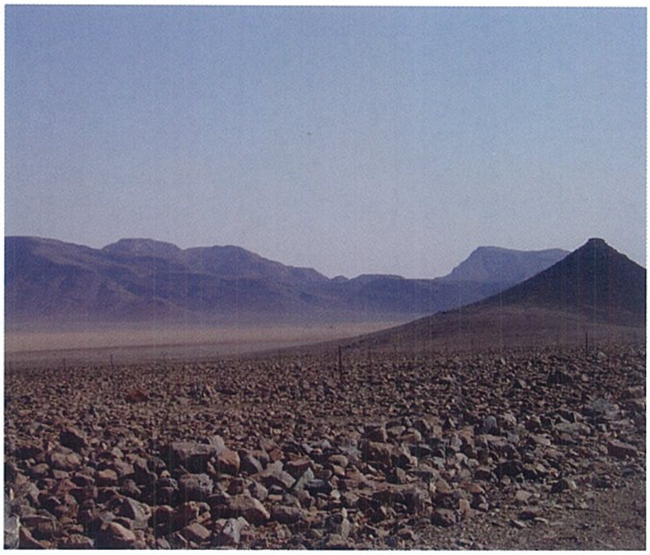


Fig. 10.14 A stony desert, Namibia

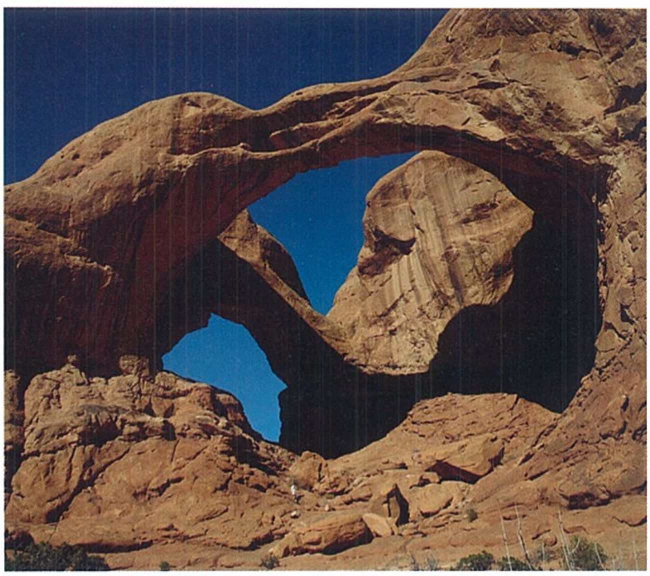


Fig. 10.15 A bare rock desert, Arches National Park, Utah, USA

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).

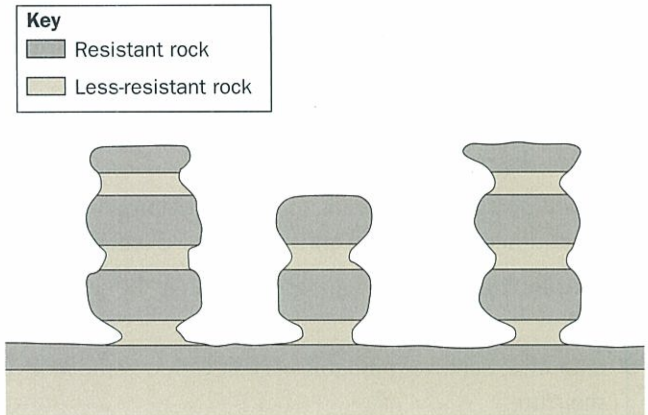


Fig. 10.18 Formation of zeugen

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:

Munḫafaḍ al-Qaṭṭārah) 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.

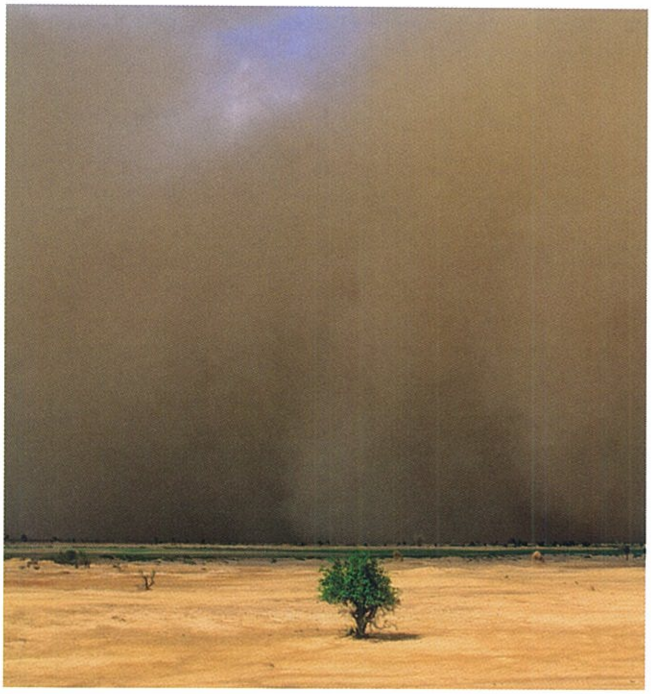


Fig. 10.20 A sandstorm in Mali

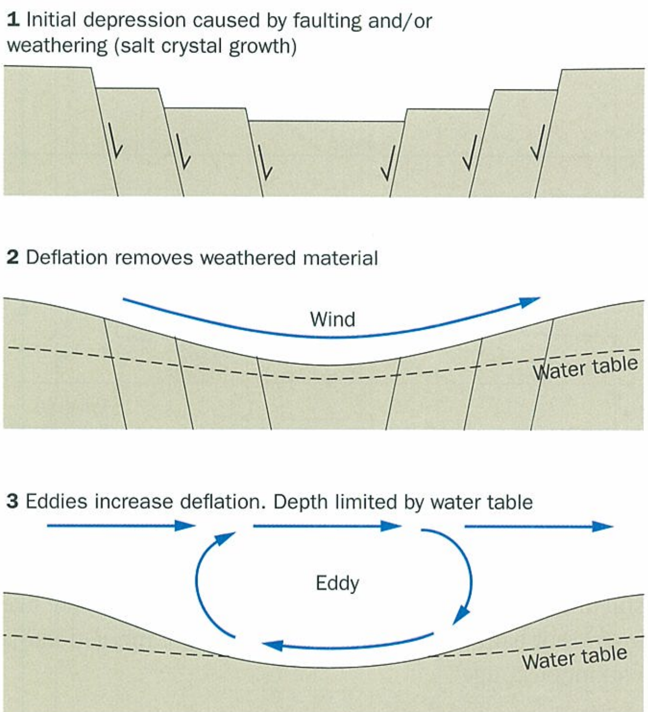


Fig. 10.21 Development of a deflation hollow

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.

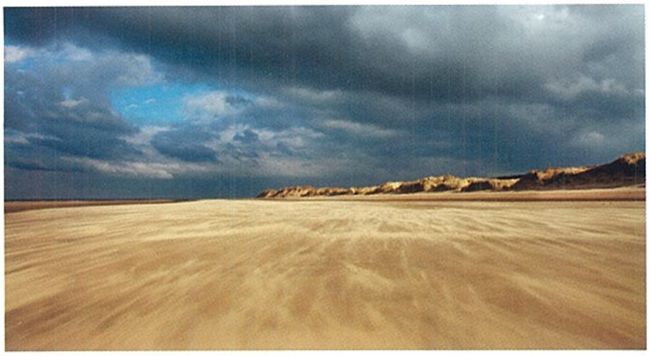


Fig. 10.22 Saltation at work

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.

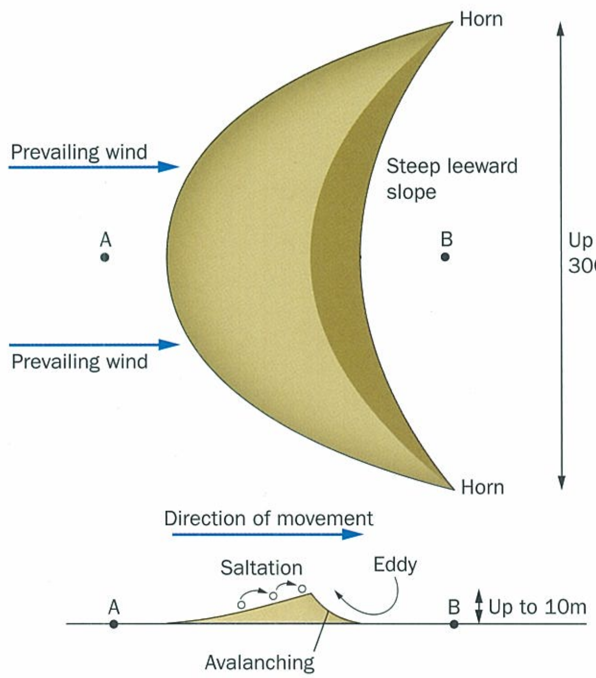


Fig. 10.24 The features of a barchan dune

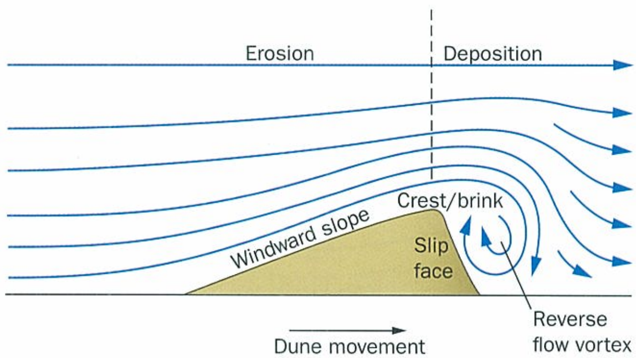


Fig. 10.25 The compression and decompression of wind streamlines over a barchan

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.

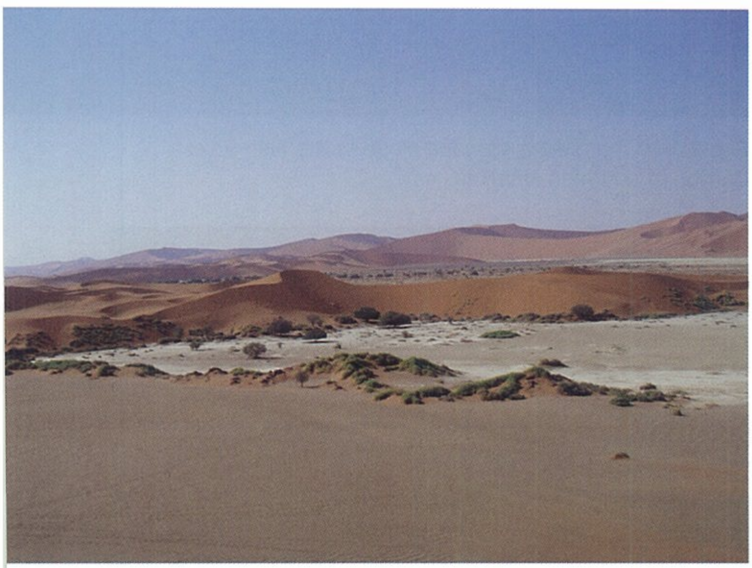


Fig. 10.27 Dunes fixed by vegetation, Sossusvlei, Namibia

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
			0
Quaternary	Neogene	Holocene Pleistocene	
			2.6
Tertiary	Neogene	Pliocene	
			5.3
Tertiary	Neogene	Miocene	
			23.0
Tertiary	Palaeogene	Oligocene	
			33.9
Tertiary	Palaeogene	Eocene	
			55.8
Tertiary	Palaeogene	Palaeocene	
			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

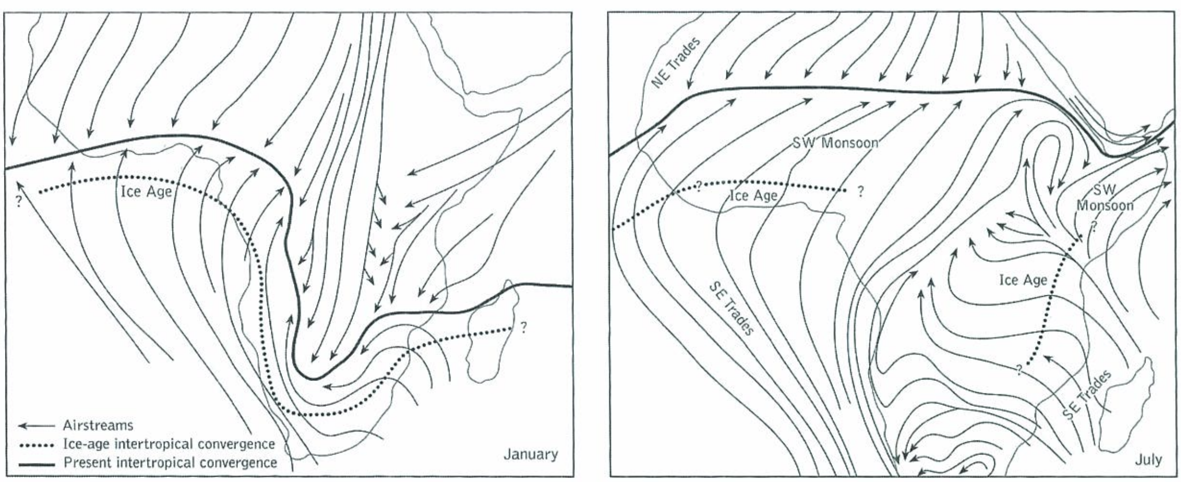


Fig. 10.31 The present position of the winds and inter-tropical convergence zone in Africa and how the pattern might have been during an glacial phase 18000 years ago

have existed in the Sahara about 130 000–100 000 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.

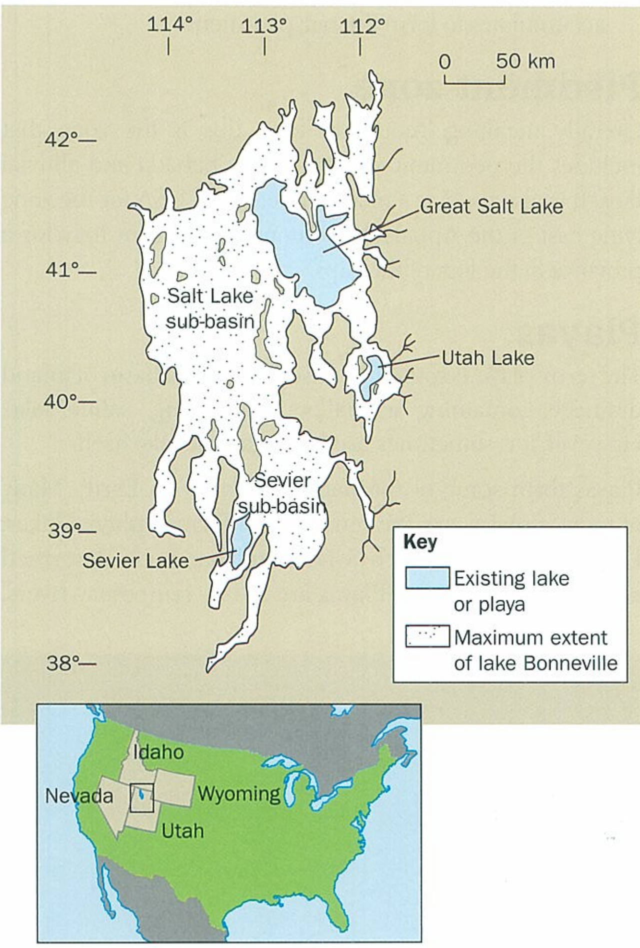


Fig. 10.32 Lake Bonneville and its remnant lakes, Utah, USA. Some of the present lakes are salt flats and not covered by water. The salt flats have been the scene of many attempts on the world land speed record

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.

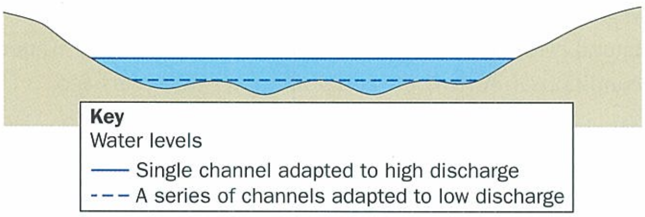


Fig. 10.34 Cross section of braided channels

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.

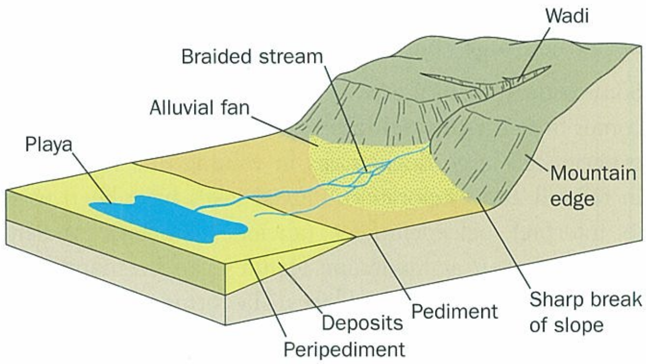


Fig. 10.35 Landforms in an inland basin of drainage in a semi-arid area

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.

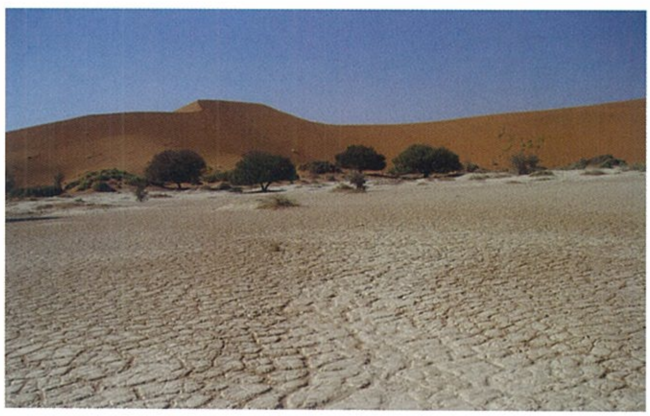


Fig. 10.36 Desiccation cracks forming on a salt crust of a playa in Namibia

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.

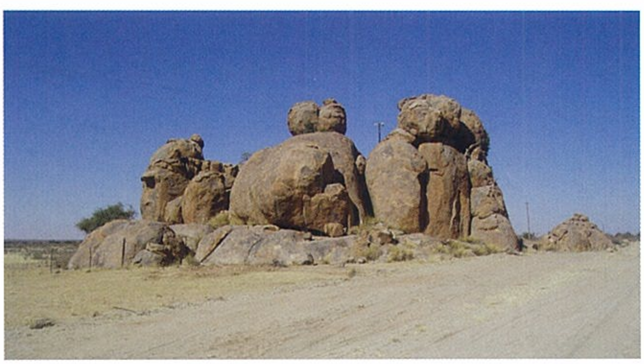


Fig. 10.37 A typical tropical kopje, Namibia

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.

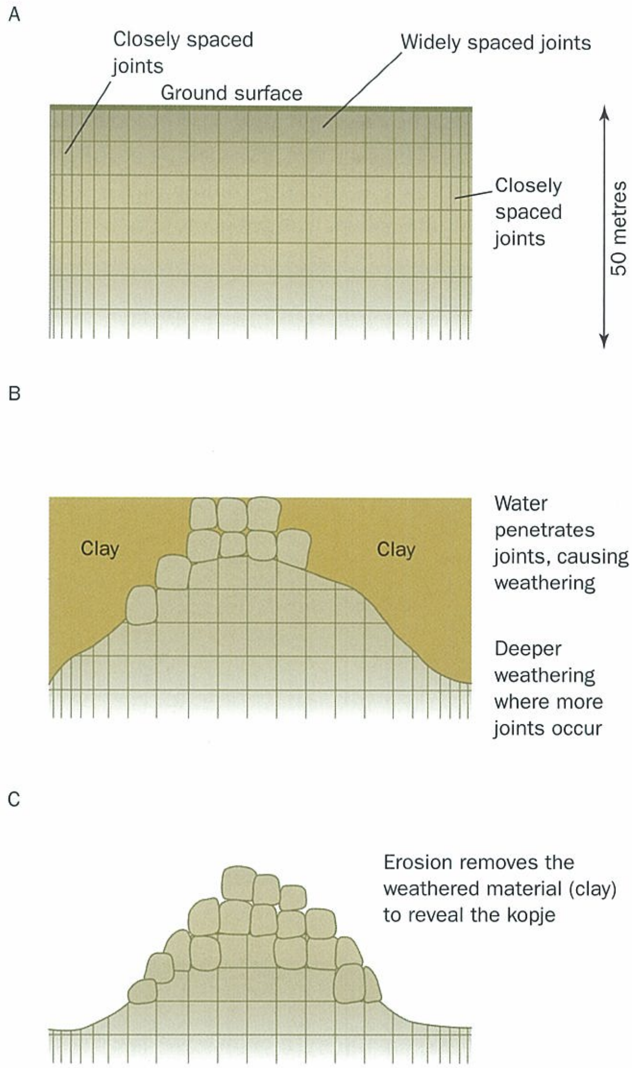


Fig. 10.38 The role of chemical weathering and erosion in the formation of kopjes

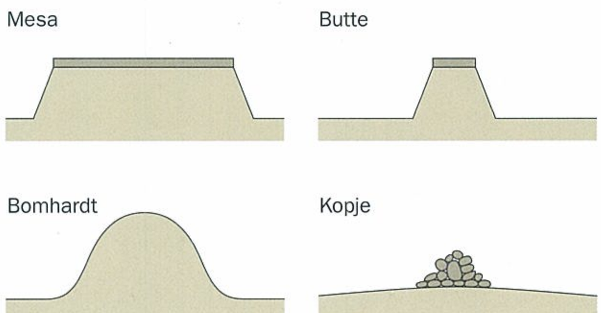


Fig. 10.39 The different forms of inselbergs

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

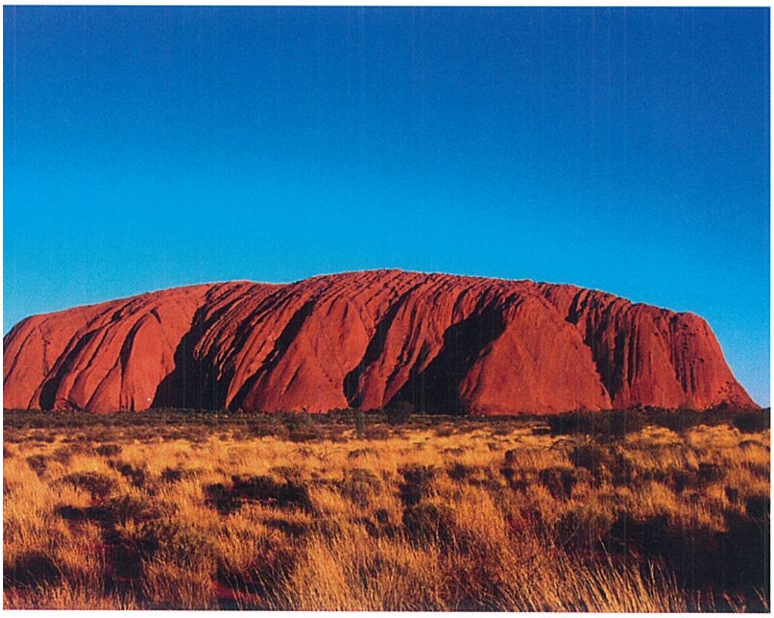


Fig. 10.41 Uluru (Ayers Rock), Northern Territory, Australia

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.

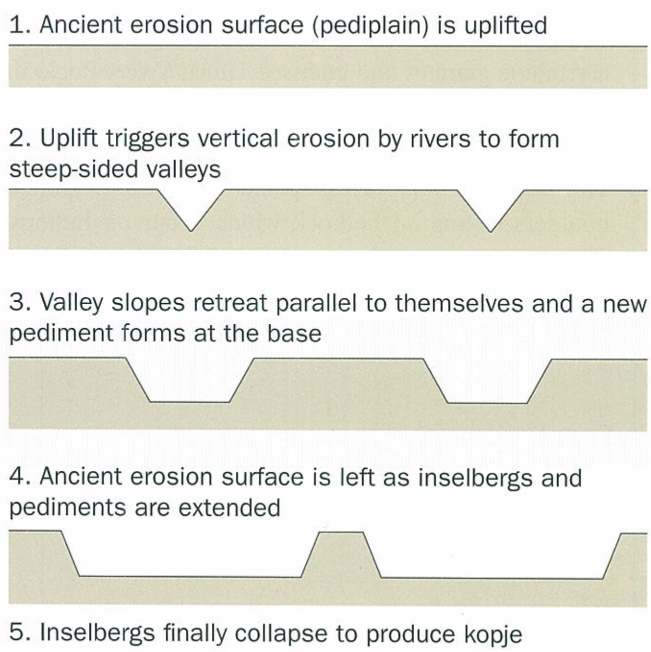


Fig. 10.43 A diagrammatic representation of the development of pediments and inselbergs through slope retreat

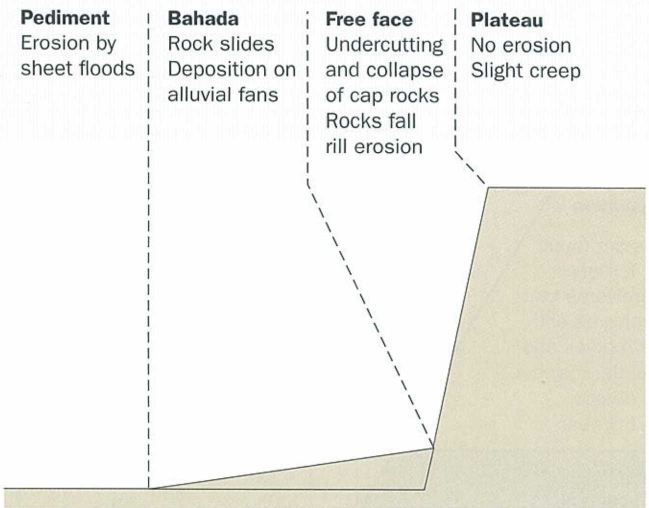


Fig. 10.44 Weathering, mass movement and erosion processes in a semi-arid landscape

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.

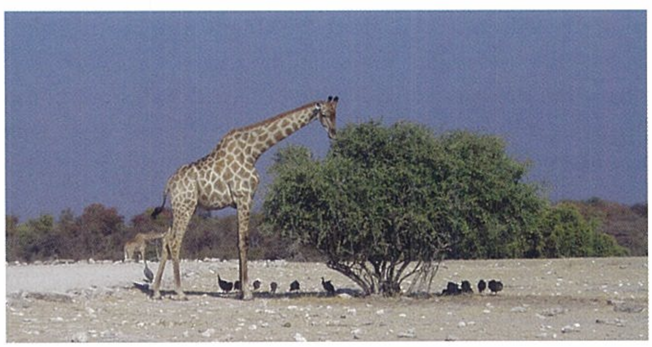


Fig. 10.47 Giraffe and guinea fowl in Namibia. Both are primary consumers

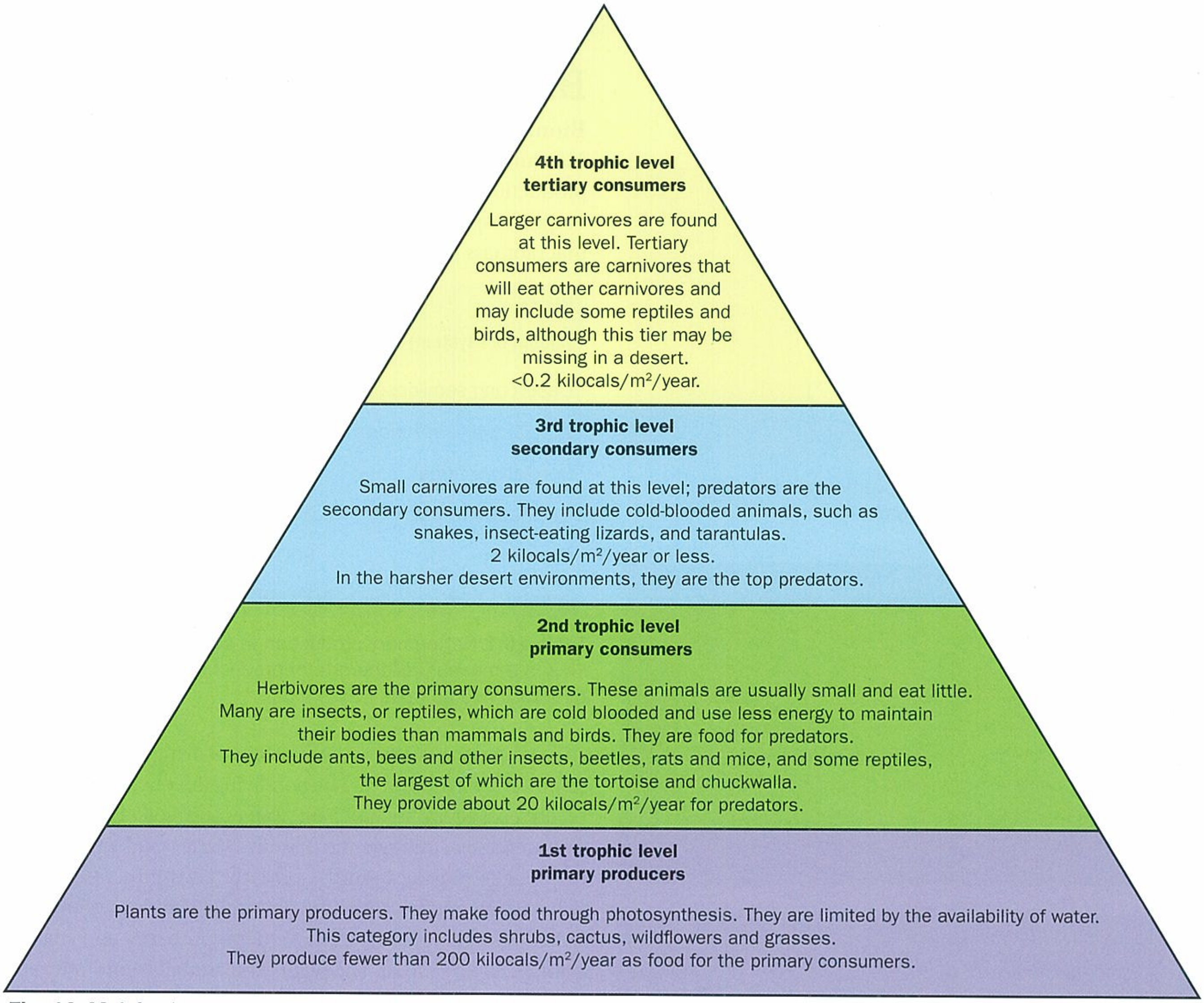


Fig. 10.46 A food pyramid in hot arid and semi-arid areas

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/m^2/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/m^2/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.

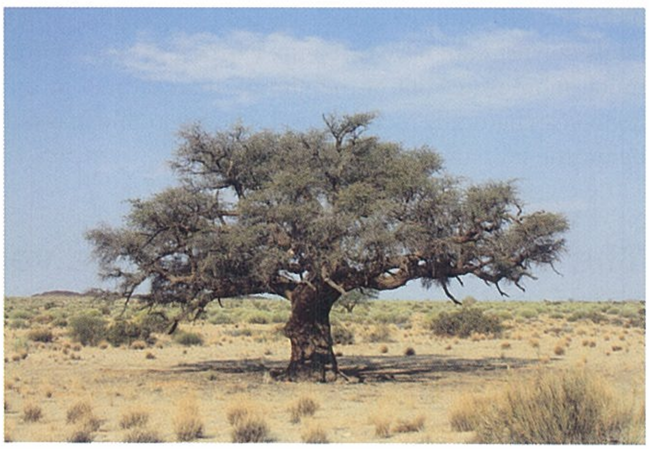


Fig. 10.48 A tree in semi-arid savanna. Notice the relatively small leaf area

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

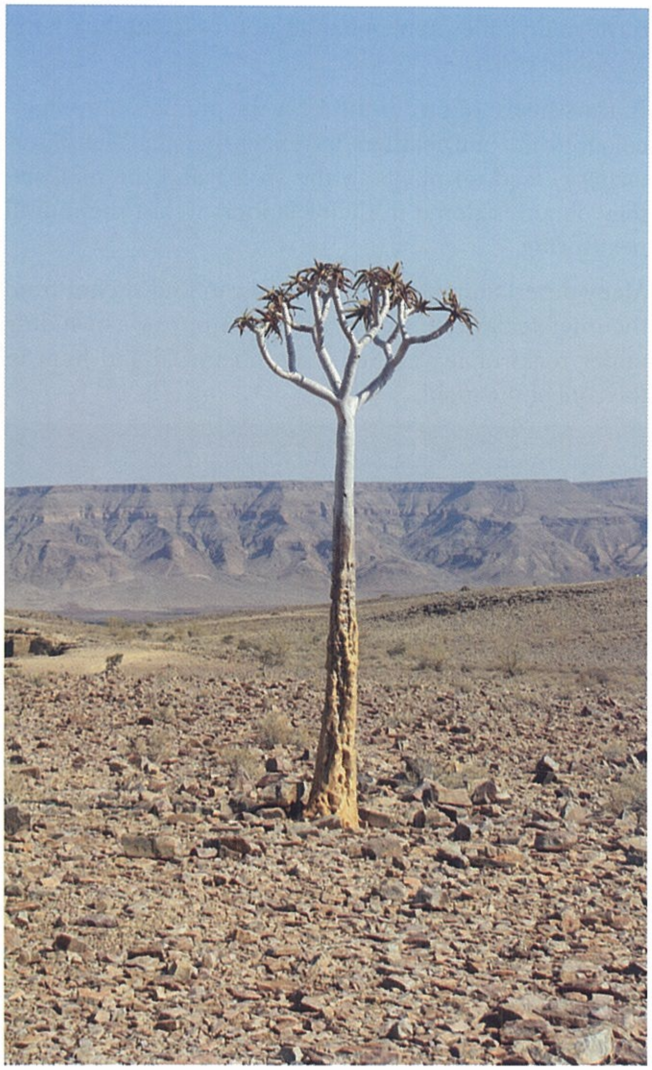


Fig. 10.51 The southern African quiver tree is, in fact, an aloe (*Aloe dichotoma*). The hollow stems were used to carry arrows, hence the name

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.

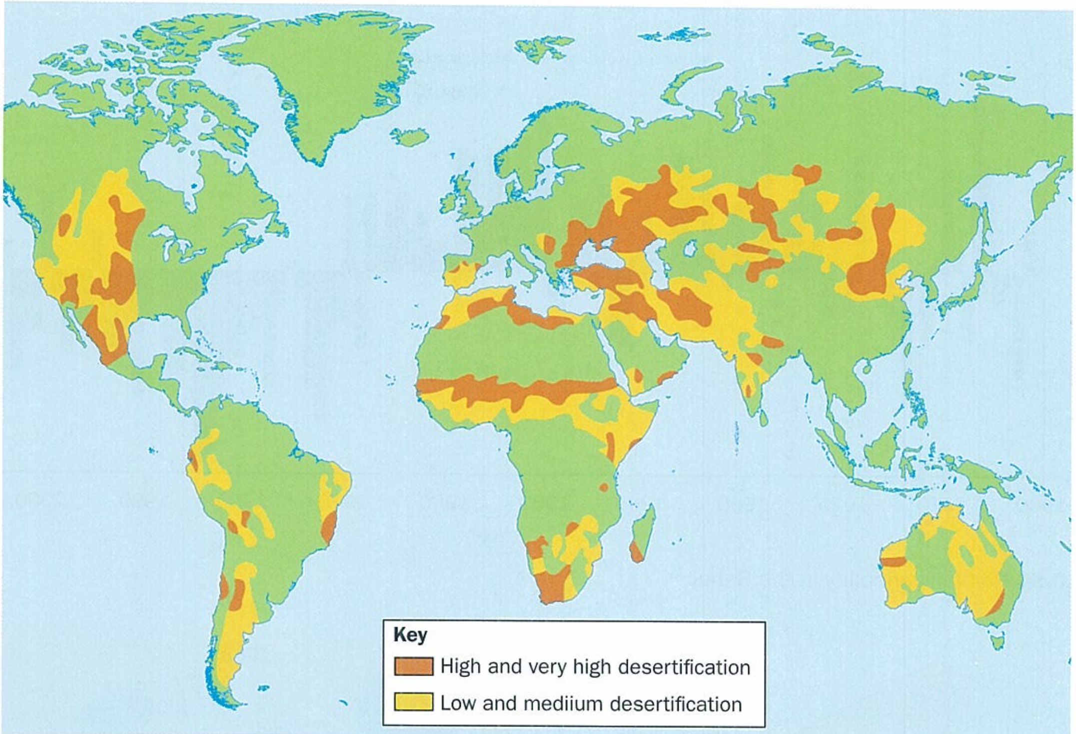


Fig. 10.52 Areas affected by desertification

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.

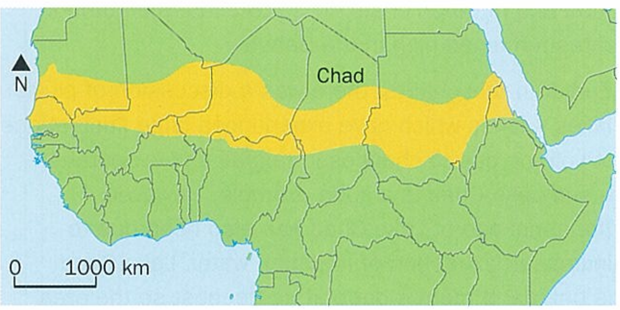


Fig. 10.53 The Sahel

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

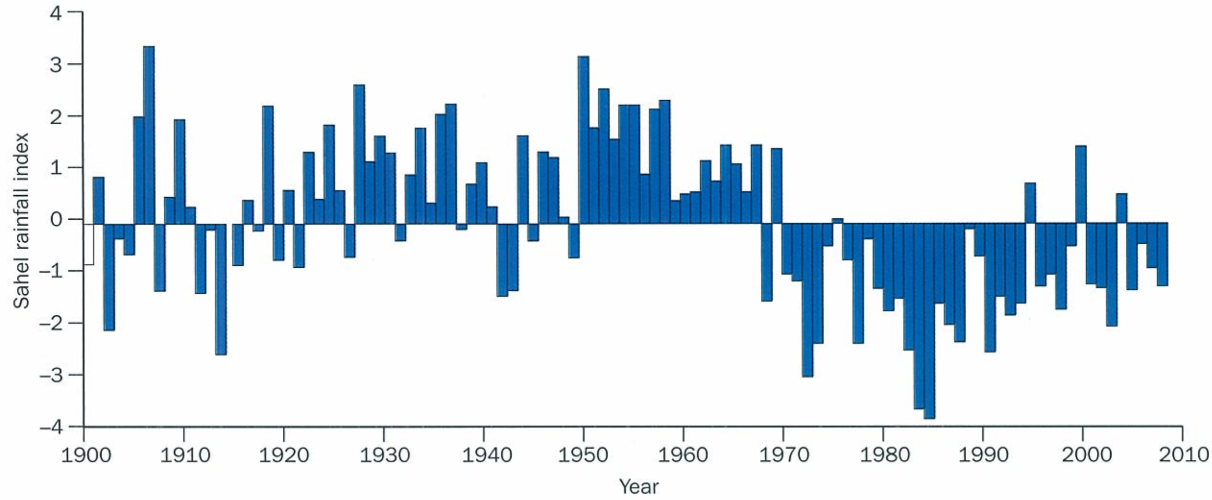


Fig. 10.54 Rainfall variability in the Sahel

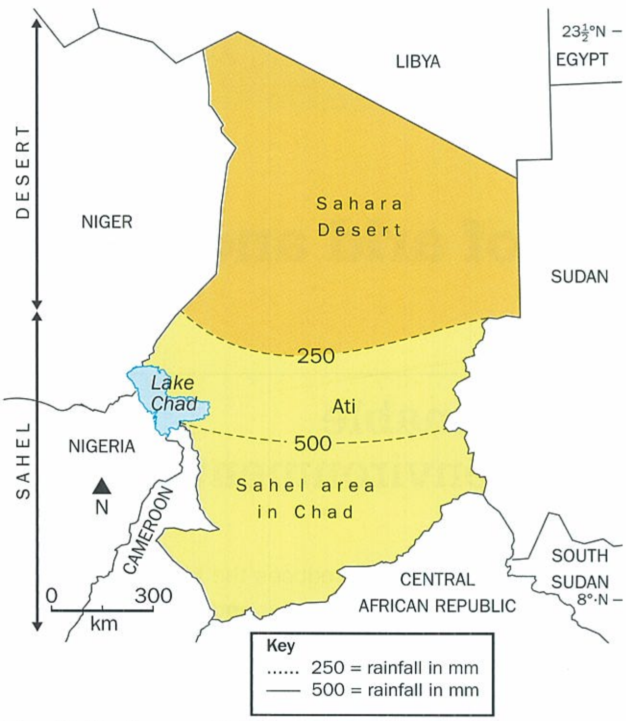


Fig. 10.55 A map of Chad

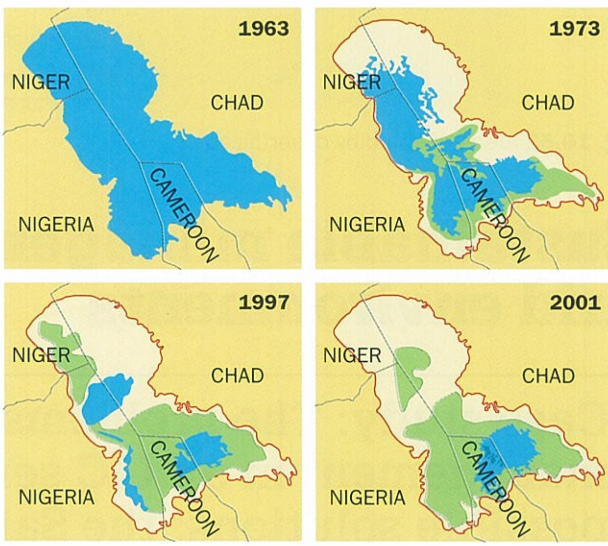


Fig. 10.56 Shrinking Lake Chad. The area in 2013 was similar to that shown for 2001

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.

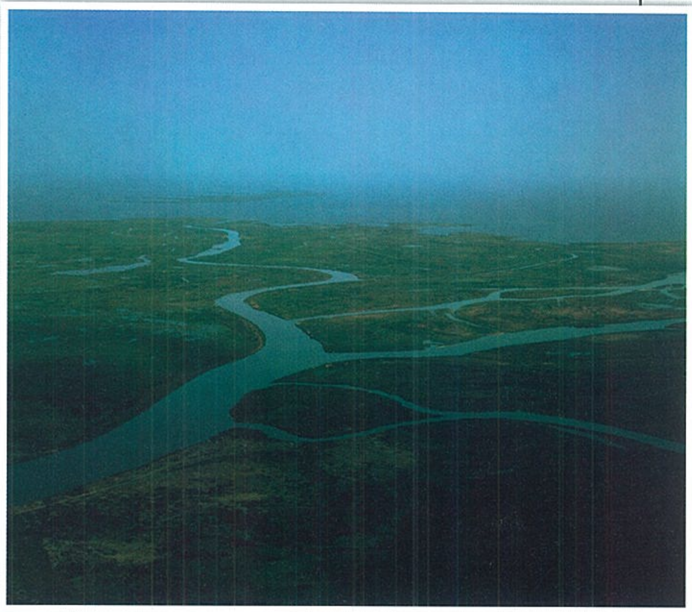


Fig. 10.57 Lake Chad from the air

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.

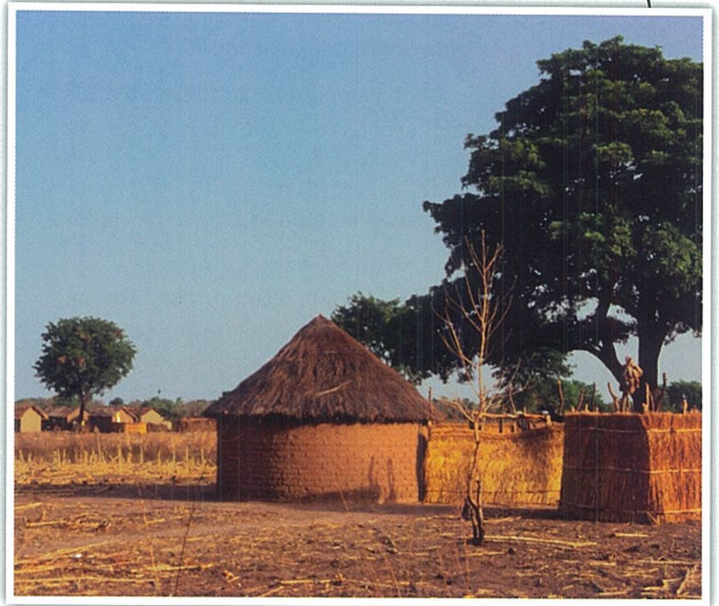


Fig. 10.59 Huts in southern Chad near Kome and Doba

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.

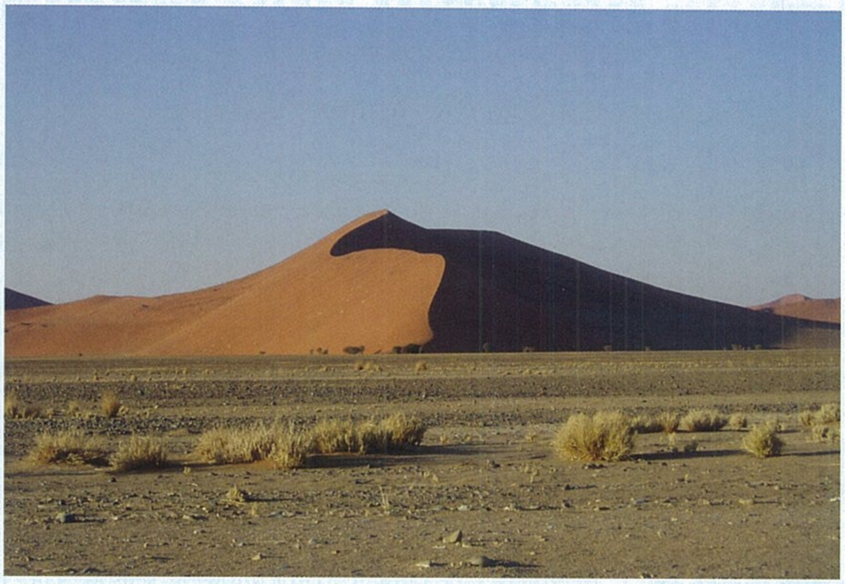


Fig. 10.61 A desert landscape in Namibia

(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]