3 Rocks and weathering

3.1 Plate tectonics

The Earth's interior

The theory of plate tectonics states that the Earth is made up of a number of layers (Figure 3.1). On the outside, there is a very thin crust, and underneath is a mantle that makes up 82 per cent of the volume of the Earth. Deeper still is a very dense and very hot core. In general, these concentric layers become increasingly more dense towards the centre. Their density is controlled by temperature and pressure. Temperature softens or melts rocks.

Close to the surface, rocks are mainly solid and brittle. This upper surface layer is known as the lithosphere, which includes the crust and the upper mantle, and is about 70 kilometres deep. The Earth's crust is commonly divided up into two main types: continental crust and oceanic crust (Table 3.1). In continental areas, silica and aluminium are very common. When combined with oxygen they make up the most common type of rock: granitic. By contrast, below the oceans the crust consists mainly of basaltic rock in which silica, iron and magnesium are most common.

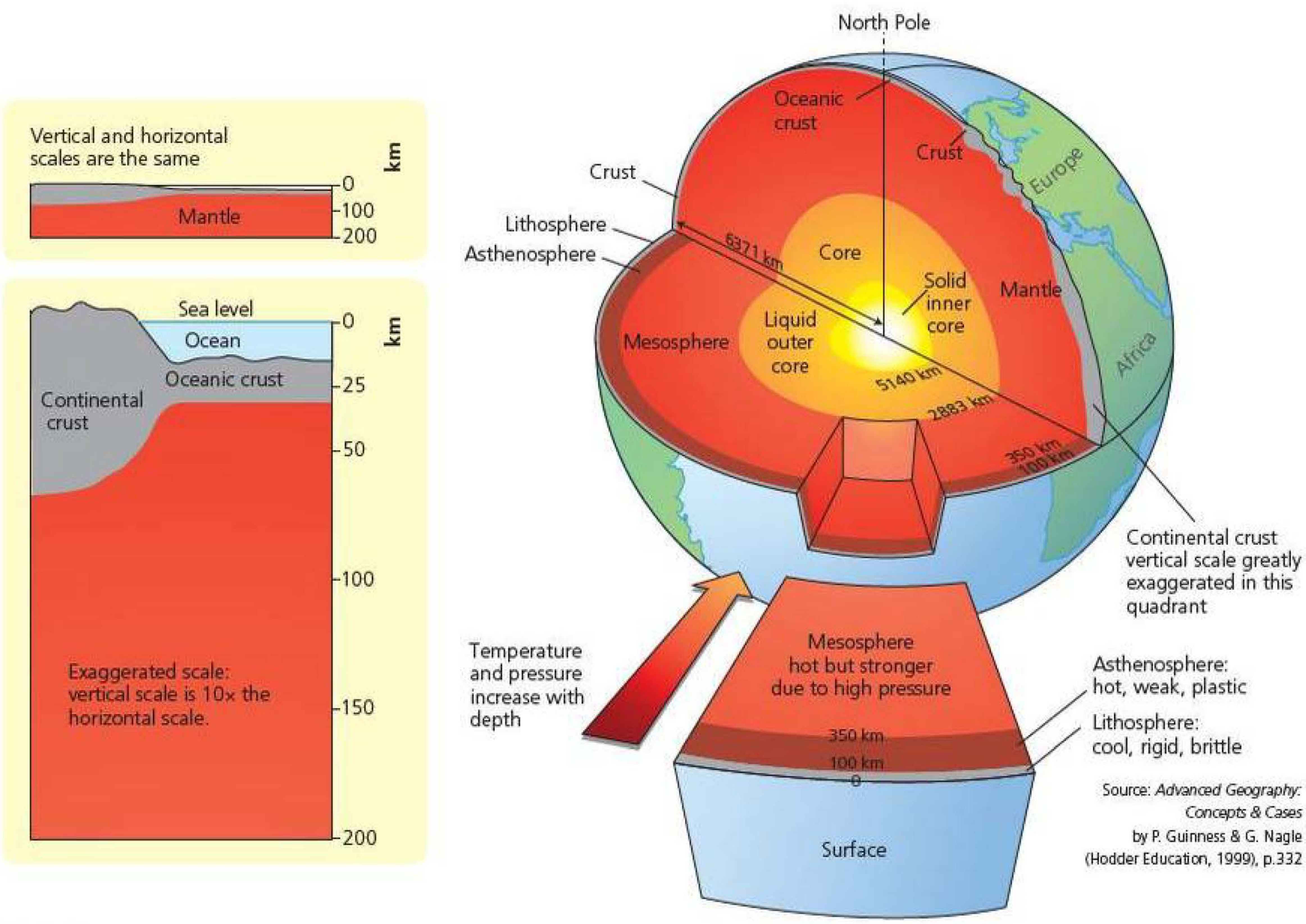


Figure 3.1 The Earth's internal structure

Table 3.1 A comparison of oceanic crust and continental crust

Examples	Continental crust	Oceanic crust
Thickness	35–70 km on average	6–10 km on average
Age of rocks	Very old; mainly over 1500 million years	Very young; mainly under 200 million years
Colour and density of rocks	Lighter, with an average density of 2.6; light in colour	Heavier, with an average density of 3.0; dark in colour
Nature of rocks	Numerous types, many contain silica and oxygen; granitic is the most common	Few types, mainly basaltic

The evidence for plate tectonics and their global patterns

In 1912, Alfred Wegener proposed the idea of continental drift. Others, such as Francis Bacon in 1620, had commented on how the shape of the coast of Africa was similar to that of South America. Wegener proposed that the continents were slowly drifting about the Earth. He suggested that, starting in the Carboniferous period some 250 million years ago, a large single continent, Pangaea, broke up and began to drift apart, forming the continents we know today. Wegener's theory provoked widespread debate initially, but with the lack of a mechanism to cause continental drift, his theory failed to receive widespread support.

In the mid-twentieth century, American Harry Hess suggested that convection currents would force molten rock (magma) to well up in the interior and to crack the crust above and force it apart. In the 1960s, research on rock magnetism supported Hess. The rocks of the Mid-Atlantic Ridge were magnetised in alternate directions in a series of identical bands on both sides of the ridge. This suggested that fresh magma had come up through the centre and forced the rocks apart. In addition, with increasing distance from the ridge the rocks were older. This supported the idea that new rocks were being created at the centre of the ridge and the older rocks were being pushed apart.

In 1965, Canadian geologist J. Wilson linked together the ideas of continental drift and sea-floor spreading into a concept of mobile belts and rigid plates, which formed the basis of plate tectonics.

The evidence of plate tectonics includes:

- the past and present distribution of earthquakes
- changes in the Earth's magnetic field
- the 'fit' of the continents: in 1620 Francis Bacon noted how the continents on either side of the Atlantic could be fitted together like a jigsaw (Figure 3.2)
- glacial deposits in Brazil match those in West Africa
- the fossil remains in India match those of Australia
- the geological sequence of sedimentary and igneous rocks in parts of Scotland match those found in Newfoundland
- ancient mountains can be traced from east Brazil to west Africa, and from Scandinavia through Scotland to Newfoundland and the Appalachians (eastern USA)
- fossil remains of a small aquatic reptile, Mesosaurus, which lived about 270 million years ago, are found only in a restricted part of Brazil and in south-west Africa – it is believed to be a poor swimmer!

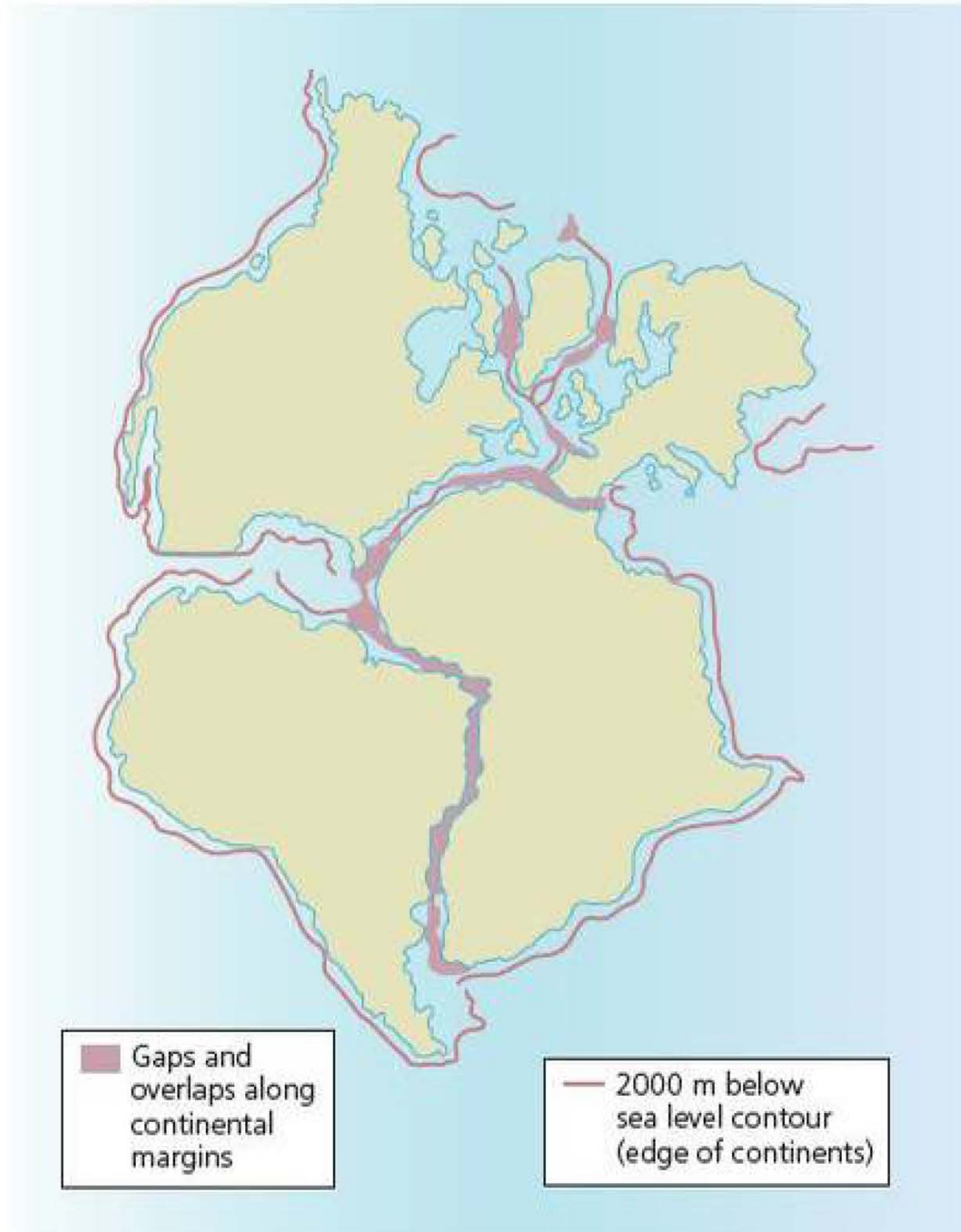
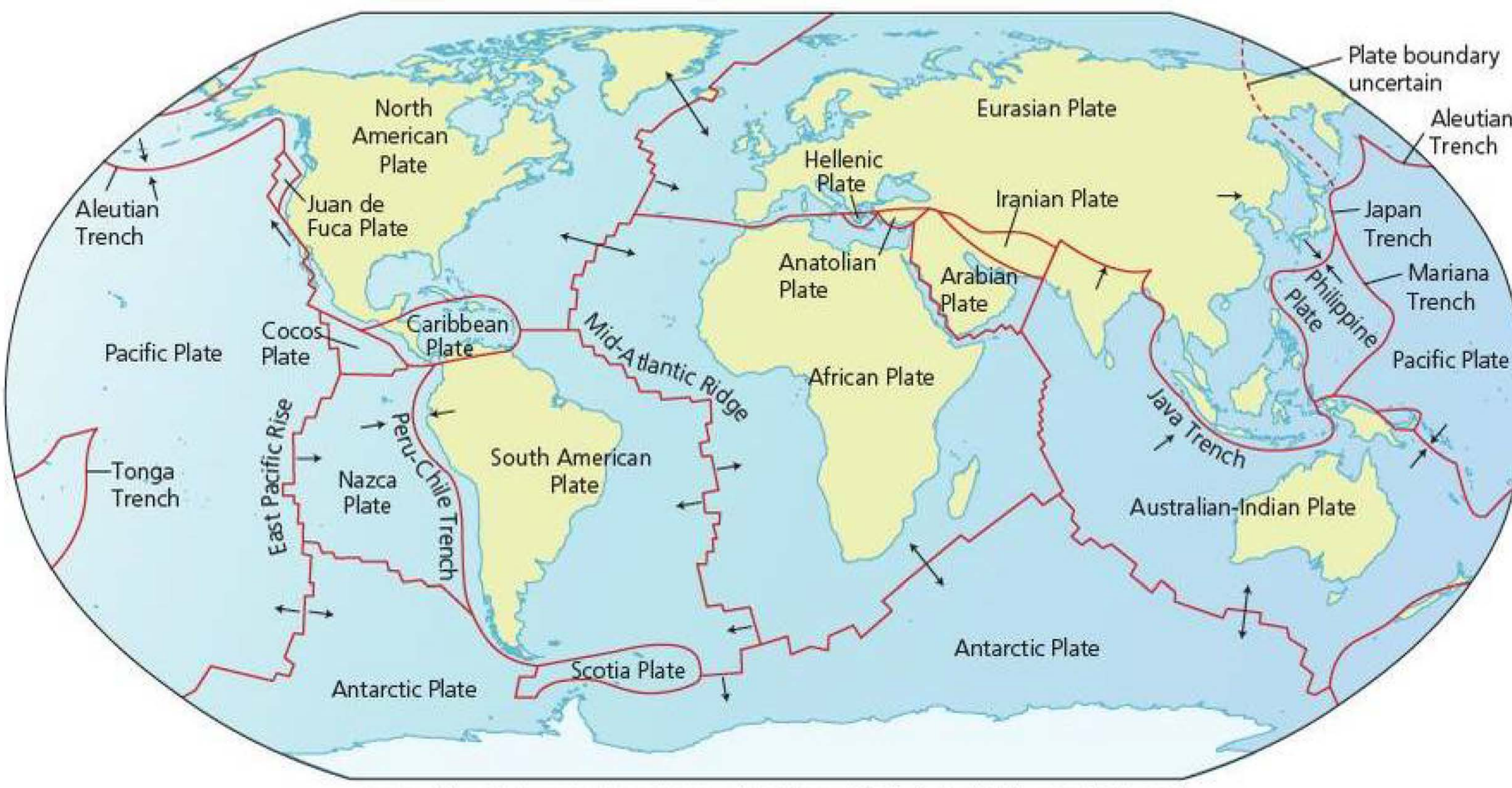


Figure 3.2 Evidence for plate tectonics

Plate boundaries

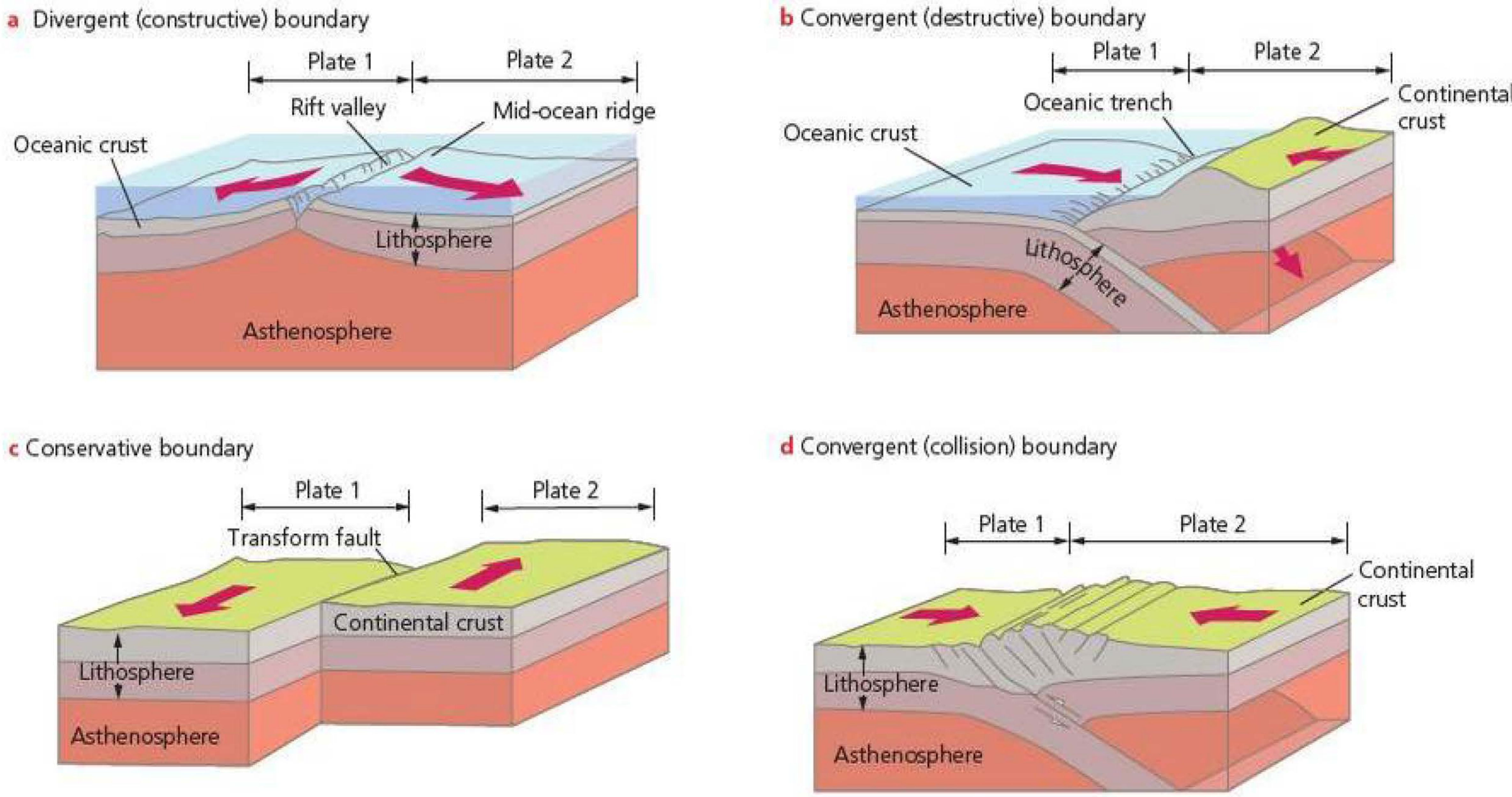
The zone of earthquakes around the world has helped to define six major plates and a number of minor plates (Figures 3.3 and 3.4). The boundaries between plates can be divided into three main types: divergent (constructive) boundaries, convergent plate boundaries (including destructive and collision boundaries) and conservative plate boundaries. Divergent (constructive) plate boundaries, where new crust is formed, are mostly in the middle of oceans (Figure 3.5a). These ridges are zones of shallow earthquakes (less than 50 kilometres below the surface). Where two plates converge, a deep-sea trench may be formed when one of the plates is subducted (forced downwards) into the mantle (Figure 3.5b). Deep earthquakes, up to 700 kilometres below the surface, are common. Good examples include the trenches off the Andes, and the Aleutian Islands that stretch out from Alaska.

Figure 3.3 Thingvellir, Iceland – a constructive plate boundary; here, the North American plate (left) is pulling away from the Eurasian plate (right of picture)



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.334

Figure 3.4 Plate boundaries



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.334

Figure 3.5 Types of plate boundary

Along some plate boundaries, plates slide past one another to create a transform fault (fault zone) without converging or diverging (Figure 3.5c). Again, these are associated with shallow earthquakes, such as the San Andreas Fault in California. Where continents embedded in the plates collide with each other, there is no subduction but collision leading to crushing, and folding may create young fold mountains such as the Himalayas and the Andes (Figure 3.5d).

The movement of plates

There are three main theories about movement:

1. **The convection current theory** – This states that huge convection currents occur in the Earth's interior. Hot magma rises through the core to the surface and then spreads out at mid-ocean ridges. The cold solidified crust sinks back into the Earth's interior, because it is heavier and denser than the surrounding material. The cause of the movement is radioactive decay in the core.
2. **The dragging theory** – Plates are dragged or subducted by their oldest edges, which have become cold and heavy. Plates are hot at the mid-ocean ridge but cool as they move away. Complete cooling takes about a million years. As cold plates descend at the trenches, pressure causes the rock to change and become heavier.
3. A hotspot is a plume of lava that rises vertically through the mantle. Most are found near plate margins and they may be responsible for the original rifting of the crust. However, the world's most abundant source of lava, the Hawaiian Hotspot, is not on a plate margin. Hotspots can cause movement – the outward flow of viscous rock from the centre may create a drag force on the plates and cause them to move.

Section 3.1 Activities

1. Briefly outline the evidence for plate tectonics.
2. Describe how a convection current works. How does it help explain the theory of plate tectonics?
3. What happens at **a** a mid-ocean ridge and **b** a subduction zone?

Processes and associated landforms

Sea-floor spreading

It was not until the early 1960s that R.S. Dietz and H.H. Hess proposed the mechanism of sea-floor spreading to explain continental drift. They suggested that continents moved in response to the growth of oceanic crust between them. Oceanic crust is thus created from the mantle at the crest of the mid-ocean ridge system.

Confirmation of the hypothesis of sea-floor spreading came with the discovery by F.J. Vine and D.H. Matthews that magnetic anomalies across the Mid-Atlantic Ridge were symmetrical on either side of the ridge axis (Figure 3.6). The only acceptable explanation for these magnetic anomalies was in terms of sea-floor spreading and the creation of new oceanic crust. When lava cools on the sea floor, magnetic grains in the rock acquire

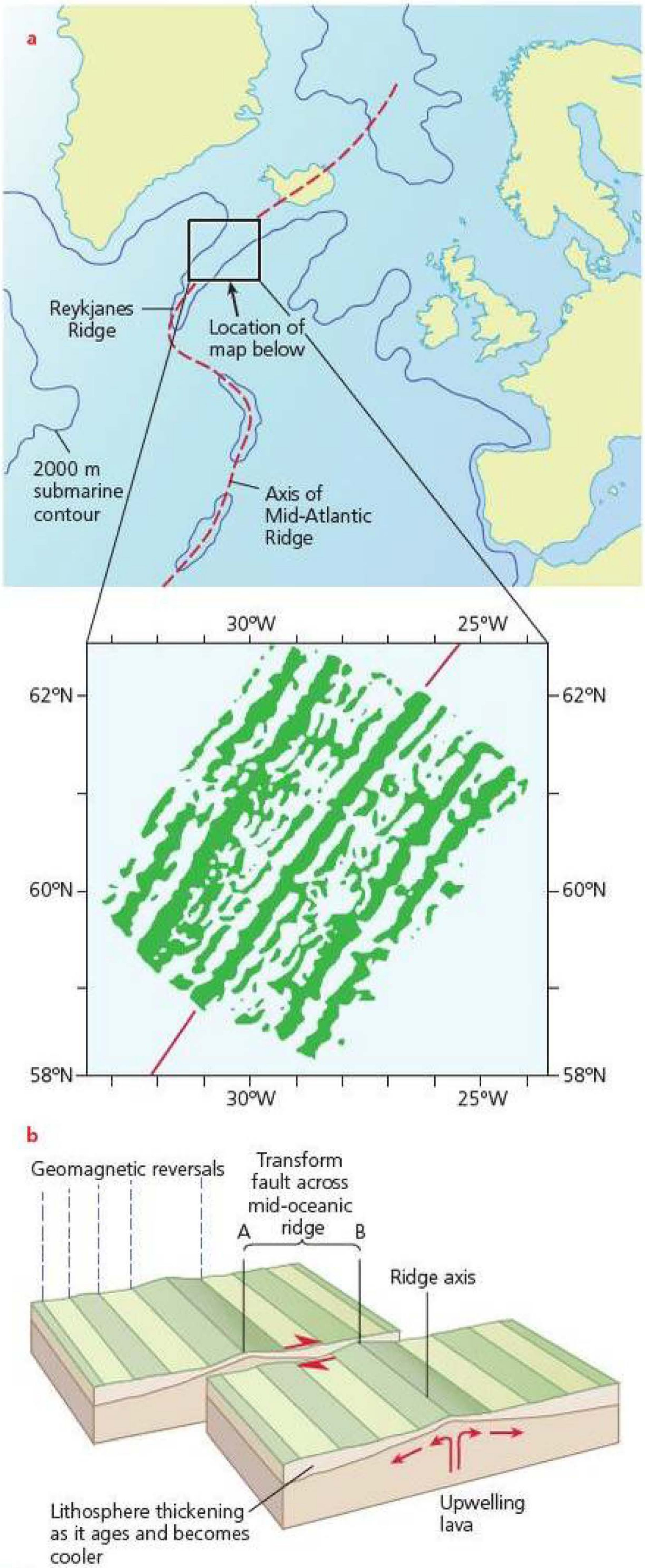


Figure 3.6 Sea-floor spreading and paleomagnetism

the direction of the Earth's magnetic field at the time of cooling. This is known as paleomagnetism.

The anomalies found across the Mid-Atlantic Ridge could, moreover, be matched with similar anomalies that had been discovered in Iceland and other parts of the world where young volcanic rocks could be dated.

The reason that the ridges are elevated above the ocean floor is that they consist of rock that is hotter and less dense than the older, colder plate. Hot mantle material wells up beneath the ridges to fill the gap created by the separating plates; as this material rises, it is decompressed and undergoes partial melting.

Spreading rates are not the same throughout the mid-ocean ridge system, but vary considerably from a few millimetres per year in the Gulf of Aden to 1 centimetre per year in the North Atlantic near Iceland and 6 centimetres per year for the East Pacific Rise. This variation in spreading rates appears to influence the ridge topography. Slow-spreading ridges, such as the Mid-Atlantic Ridge, have a pronounced rift down the centre. Fast-spreading ridges, such as the East Pacific Rise, lack the central rift and have a smooth topography. In addition, spreading rates have not remained constant through time.

The main reason for the differences in spreading rates is that the slow-spreading ridges are fed by small and discontinuous magma chambers, thereby allowing for the eruption of a comparatively wide range of basalt types. Fast-spreading ridges have large, continuous magma chambers that generate comparatively similar magmas. Because of the higher rates of magma discharge, sheet lavas are more common.

Although mid-ocean ridges appear at first sight to be continuous features within the oceans, they are all broken into segments by transverse fractures (faults) that displace the ridges by tens or even hundreds of kilometres.

Section 3.1 Activities

Briefly explain what is meant by **a** *paleomagnetism* and **b** *sea-floor spreading*.

Fractures are narrow, linear features that are marked by near-vertical fault planes.

Subduction zones and ocean trenches

Subduction zones form where an oceanic lithospheric plate collides with another plate, whether continental or oceanic (Figure 3.7). The density of the oceanic plate is similar to that of the **asthenosphere**, so it can be easily pushed down into the upper mantle. Subducted (lithospheric) oceanic crust remains cooler, and therefore denser than the surrounding mantle, for millions of years; so once initiated, subduction carries on, driven, in part, by the weight of the subducting crust. As the Earth has not grown significantly in size – not enough to accommodate

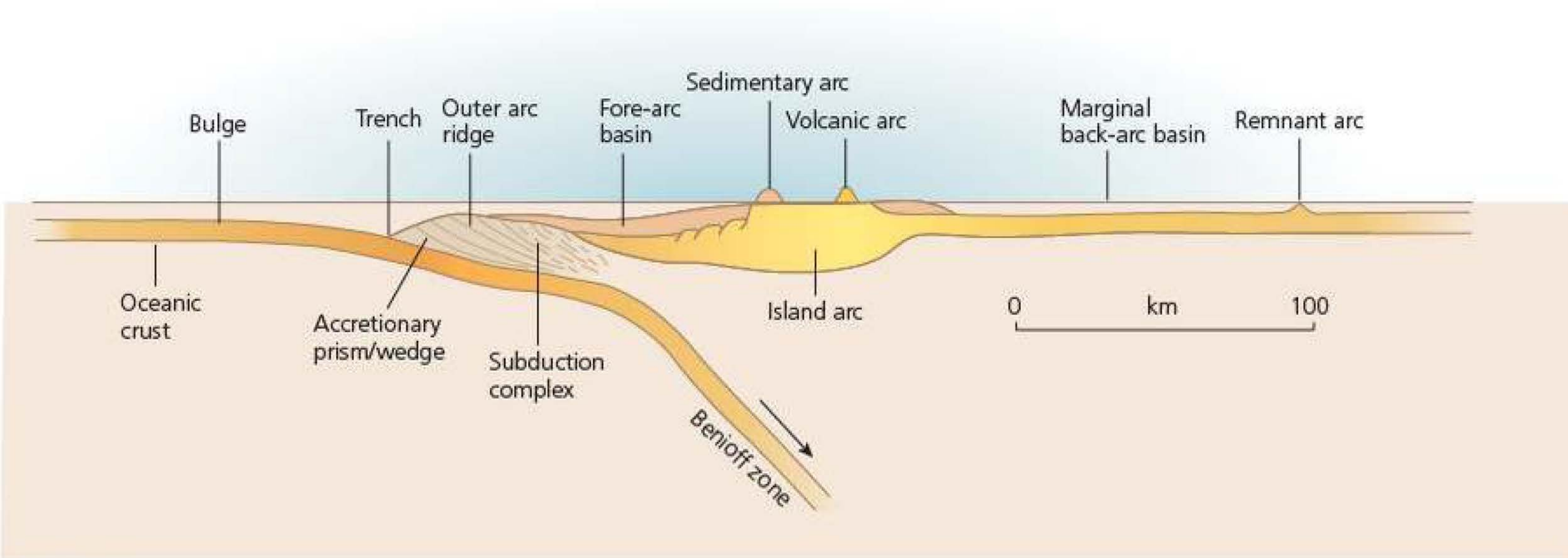


Figure 3.7 Ocean–ocean subduction zone

the new crustal material created at mid-ocean ridges – the amount of subduction roughly balances the amount of production at the constructive plate margins.

Subduction zones dip mostly at angles between 30° and 70°, but individual subduction zones dip more steeply with depth. The dip of the slab is related inversely to the velocity of convergence at the trench, and is a function of the time since the initiation of subduction. The older the crust, the steeper it dips. Because the downgoing slab of lithosphere is heavier than the plastic asthenosphere below, it tends to sink passively; and the older the lithosphere, the steeper the dip.

The evidence for subduction is varied:

- the existence of certain landforms such as deep-sea trenches and folded sediments – normally arc-shaped and containing volcanoes
- the **Benioff zone** – a narrow zone of earthquakes dipping away from the deep-sea trench
- the distribution of temperature at depth – the oceanic slab is surrounded by higher temperatures.

At the subduction zone, deep-sea **ocean trenches** are found. Deep-sea trenches are long, narrow depressions in the ocean floor with depths from 6000 metres to 11 000 metres. Trenches are found adjacent to land areas and associated with island arcs worldwide. They are more numerous in the Pacific Ocean. The trench is usually asymmetric, with the steep side towards the land mass. Where a trench occurs off a continental margin, the turbidites (sediments) from the slope are trapped, forming a hadal plain on the floor of the trench.

Benioff zone

A large number of events take place on a plane that dips on average at an angle of about 45° away from the underthrusting oceanic plate. The plane is known as the Benioff (or Benioff-Wadati) zone, after its discoverer(s), and earthquakes on it extend from the surface, at the trench, down to a maximum depth of about 680 kilometres. For example, shallow, intermediate and deep-focus earthquakes in the south-western Pacific occur at progressively greater distances away from the site of underthrusting at the Tonga Trench.

Section 3.1 Activities

Describe the main characteristics of **a** mid-ocean ridges and **b** subduction zones.

Fold-mountain building

Plate tectonics is associated with mountain building. Linear or arcuate chains – sometimes called 'orogenic mountain belts' – are associated with convergent plate boundaries, and formed on land. Where an ocean plate meets a continental plate, the lighter, less dense continental plate may be folded and buckled into fold mountains, such as the Andes. Where two continental plates meet, both may be folded and buckled, as in the case of the Himalayas, formed by the collision of the Eurasian and Indian plates. Mountain building is often associated with crustal thickening, deformation and volcanic activity, although in the case of the Himalayas, volcanic activity is relatively unimportant.

The Indian subcontinent moved rapidly north during the last 70 million years, eventually colliding with the main body of Asia. A huge ocean (Tethys) has been entirely lost between these continental masses. Figure 3.8a shows the situation just prior to the elimination of the Tethys Ocean by subduction beneath Asia. Note the volcanic arc on the Asian continent (rather like the Andes today).

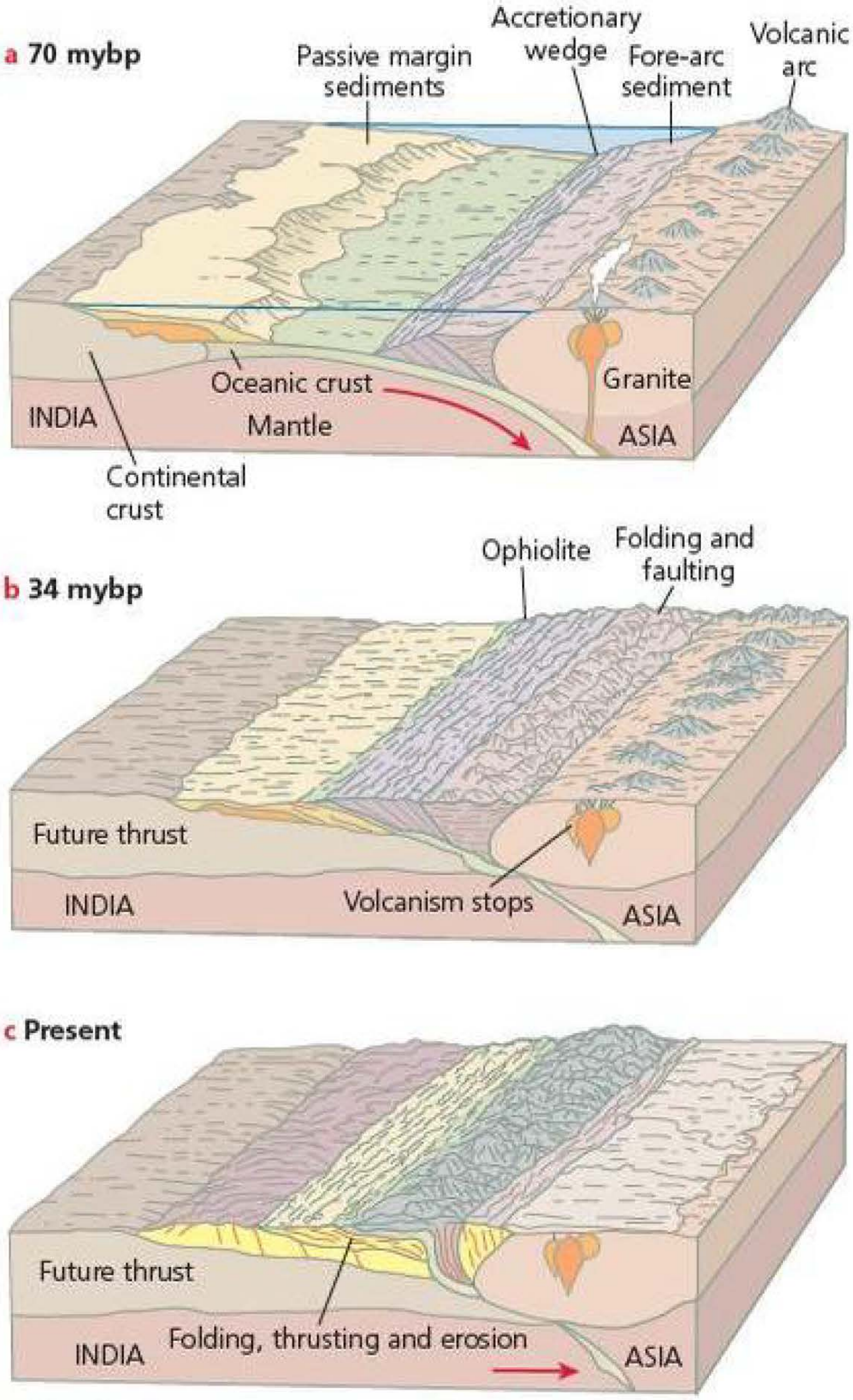


Figure 3.8 Formation of the Himalayas

In Figure 3.8b, the Tethys Ocean has *just* closed. The leading edge of the Indian subcontinent and the sedimentary rocks of its continental shelf have been thrust beneath the edge of the Asian continent. (Ophiolite refers to pieces of ocean crust thrusted onto the edge of the continental crust.)

Finally, in Figure 3.8c the Indian subcontinent continues to move north-eastward relative to the rest of Asia. In the collision zone, the continental crust is thickened because Asia overrides India, and it is this crustal thickening that results in the uplift of the Himalayan mountain range. The red lines show the many locations in the collision zone where thrust faults are active to accommodate the deformation and crustal thickening.

In contrast, the Andes were formed as a result of the subduction of oceanic crust under continental crust. The Andes are the highest mountain range in the Americas, with 49 peaks over 6000 metres high. Unlike the Himalayas, the Andes contain many active volcanoes.

Before about 250 million years ago, the western margin of South America was a passive continental margin. Sediments accumulated on the continental shelf and slope. With the break-up of Pangaea, the South American plate moved westward, and the eastward-moving oceanic lithosphere began subducting beneath the continent.

As subduction continued, rocks of the continental margin and trench were folded and faulted and became part of an accretionary wedge along the west coast of South America. Subduction also resulted in partial melting of the descending plate, producing andesitic volcanoes at the edge of the continent.

The Andes mountains comprise a central core of granitic rocks capped by andesitic volcanoes. To the west of this central core, along the coast, are the deformed rocks of the accretionary wedge; and to the east of the central core are sedimentary rocks that have been intensely folded. Present-day subduction, volcanism and seismicity indicate that the Andes mountains are still actively forming.

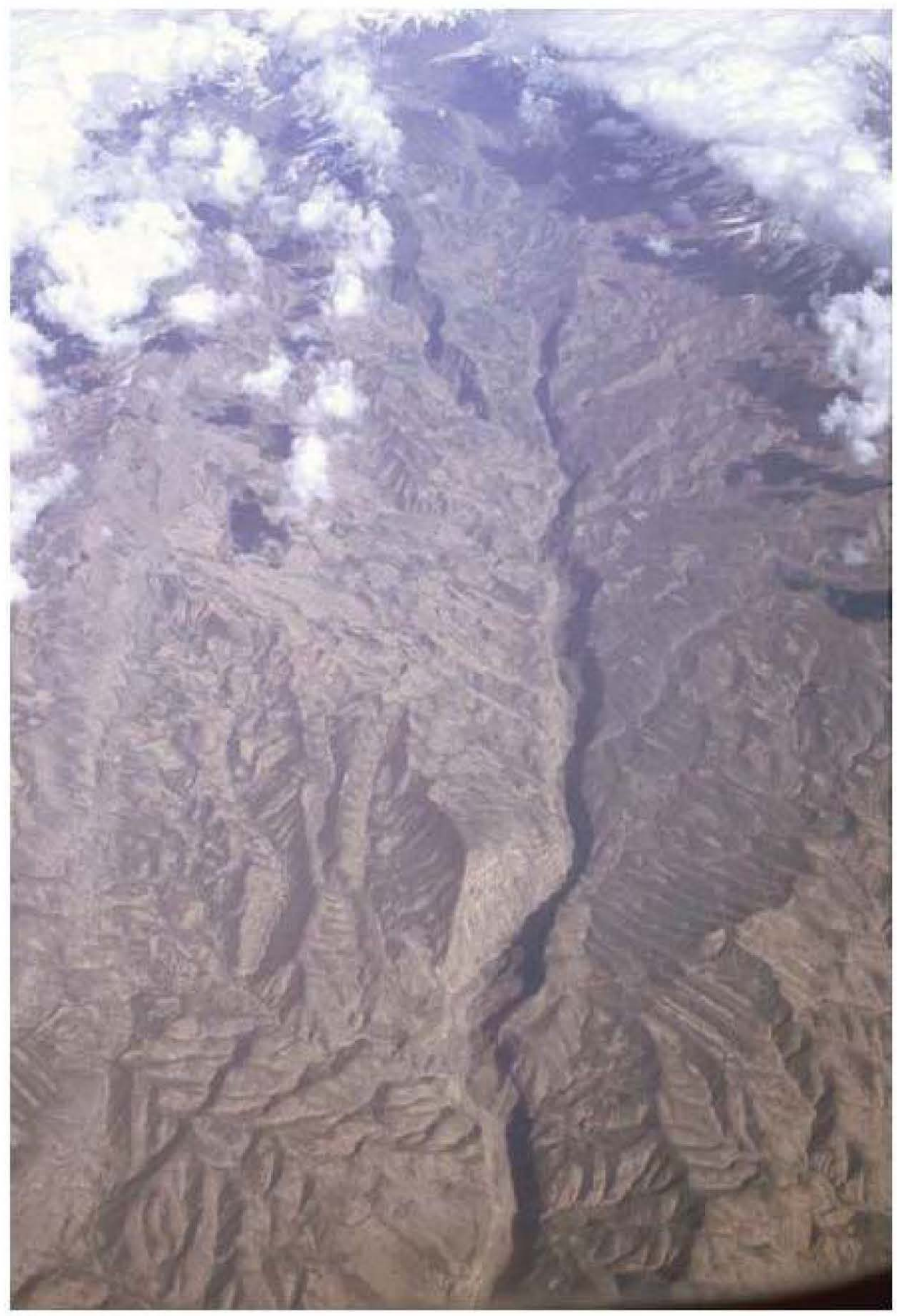


Figure 3.9 Fold mountains

Section 3.1 Activities

Compare and contrast the formation of the Andes and the formation of the Himalayas.

Ocean ridges

The longest linear, uplifted features of the Earth's surface are to be found in the oceans. They are giant submarine mountain chains with a total length of more than 60000 kilometres, between 1000 and 4000 kilometres wide and have crests that rise 2 to 3 kilometres above the surrounding ocean basins, which are 5 kilometres deep. The average depth of water over their crests is thus about 2500 metres. These features are the mid-ocean ridges, famous now not only for their spectacular topography, but because it was with them, in the early 1960s, that the theory of ocean-floor spreading, the precursor of plate tectonic theory, began. We now know that it is at these mid-ocean ridges that new lithosphere is created.

Similar ridges occur at the margins of oceans; the East Pacific Rise is an example. There are other spreading ridges behind the volcanic arcs of subduction zones. These are usually termed 'back-arc spreading centres'. The first ridge to be discovered, the Mid-Atlantic Ridge, was found during attempts to lay a submarine cable across the Atlantic in the mid-nineteenth century.

Volcanic island arcs

Island arc systems are formed when oceanic lithosphere is subducted beneath oceanic lithosphere. They are consequently typical of the margins of shrinking oceans such as the Pacific, where the majority of island arcs are located. They also occur in the western Atlantic, where the Lesser Antilles (Caribbean) and Scotia arcs are formed at the eastern margins of small oceanic plates. The Lesser Antilles (Eastern Caribbean) Arc shows all the features of a typical island arc. Ocean–ocean subduction zones tend to be simpler than ocean–continental subduction zones. In a typical ocean–ocean subduction zone, there are a number of characteristic features (Figure 3.10):

- Ahead of the subduction zone, there is a low bulge on the sea floor (known as the **trench outer rise**) caused by the bending of the plate as it subducts. One of the best-known features is the trench that marks the boundary between the two plates. In the Eastern Caribbean, the trench associated with the subduction zone is largely filled with sediment from the Orinoco River. These sediments, more than 20 kilometres thick, have been deformed and folded into the Barbados Ridge, which emerges above the sea at Barbados.
- The **outer slope** of the trench is generally gentle, but broken by faults as the plate bends. The floor of the trench is often flat and covered by sediment (turbidites) and ash. The trench **inner slope** is steeper and contains fragments of the subducting plate, scraped off like shavings from a carpenter's plane. The **subduction complex** (also known as **accretionary prisms**) is the slice of the descending slab and may form significant landforms – for example in the Lesser Antilles, the islands of Trinidad, Tobago and Barbados are actually the top of the subduction complex.
- Most subduction zones contain an **island arc**, located parallel to a trench on the overriding plate. Typically they are found some 150–200 kilometres from the trench. Volcanic island arcs such as those in the Caribbean, including the islands from Grenada to St Kitts, are island arcs above sea level.

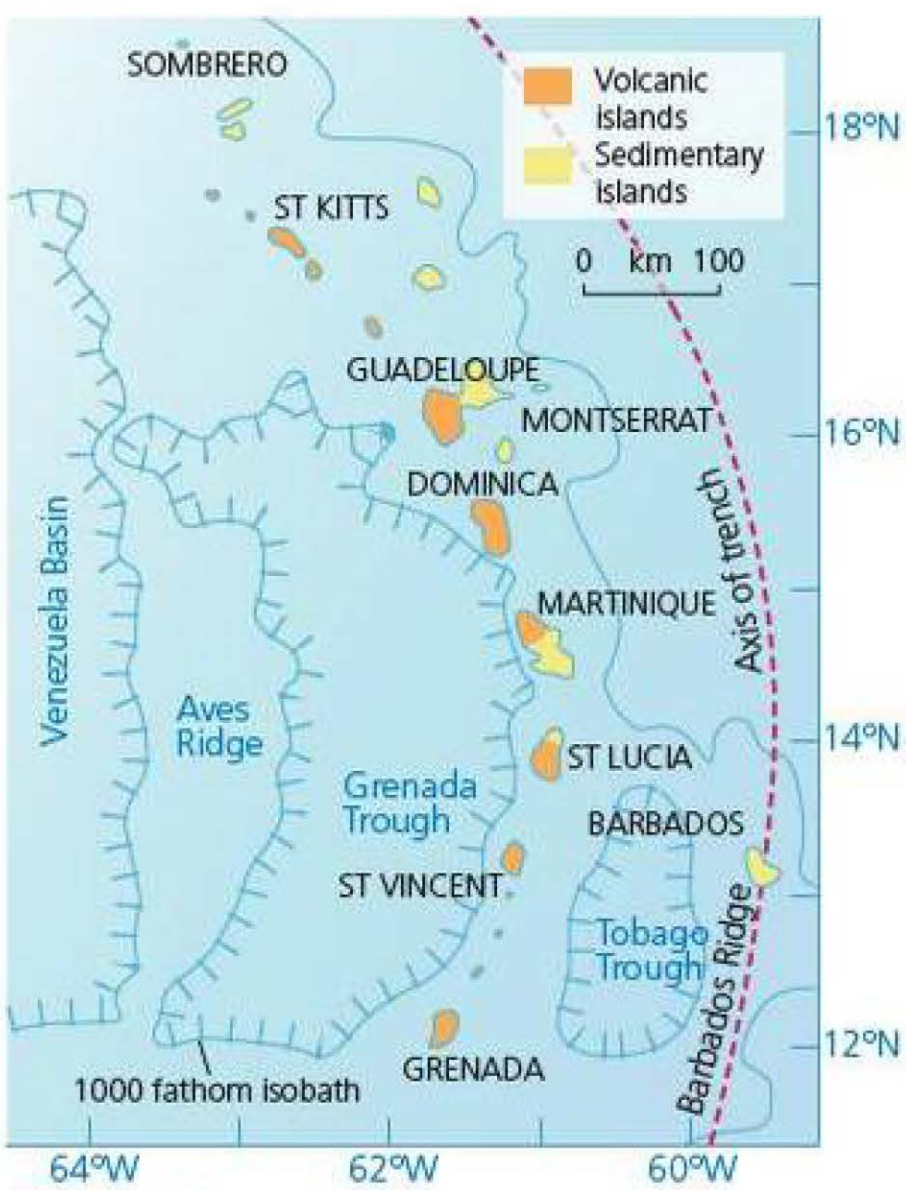


Figure 3.10 Island arcs in the Caribbean

Volcanic activity on Montserrat

Section 3.1 Activities

1 Describe the main features of an island arc system.
2 Briefly explain how island arcs are formed.

3.2 Weathering and rocks

Weathering is the decomposition and disintegration of rocks *in situ*. Decomposition refers to chemical weathering and creates altered rock substances, such as kaolinite (china clay) from granite. By contrast, disintegration or mechanical weathering produces smaller, angular fragments of the same rock, such as scree. A third type, biological weathering, has been identified, whereby plants and animals chemically alter rocks and physically break rocks through their growth and movement. Biological weathering is not a separate type of weathering, but a form of disintegration and decomposition. It is important to note that these processes are interrelated rather than operating in isolation.

Weathering is central to landscape evolution, as it breaks down rock and enables erosion and transport. A number of key features can be recognised:

- Many minerals are formed under high pressure and high temperatures in the Earth's core. As they cool, they become more stable.
- Weathering produces irreversible changes in a rock. Some rocks change from a solid state to a fragmented or clastic state, such as scree. Others are changed to a pliable or plastic state, such as clay.
- Weathering causes changes in volume, density, grain size, surface area, permeability, consolidation and strength.
- Weathering forms new minerals and solutions.
- Some minerals, such as quartz, may resist weathering.
- Minerals and salts may be removed, transported, concentrated or consolidated.
- Weathering prepares rocks for subsequent erosion and transport.
- New landforms and features are produced.

Physical/mechanical weathering

There are four main types of mechanical weathering: freeze–thaw (ice crystal growth), salt crystal growth, disintegration and pressure release. Mechanical weathering operates at or near the Earth's surface, where temperature changes are most frequent.

Freeze–thaw (also called 'ice crystal growth' or 'frost shattering') occurs when water in joints and cracks freezes at 0 °C. It expands by about 10 per cent and exerts pressure up to a maximum of 2100 kg/cm² at –22 °C. These pressures greatly exceed most rocks' resistance (Table 3.2). However, the average pressure reached in freeze–thaw is only 14 kg/cm².

Table 3.2 Resistance to weathering

Rock	Resistance (kg/cm²)
Marble	100
Granite	70
Limestone	35
Sandstone	7–14

Freeze–thaw is most effective in environments where moisture is plentiful and there are frequent fluctuations above and below freezing point. Hence it is most effective in periglacial and alpine regions. Freeze–thaw is most rapid when it operates in connection with other processes, notably pressure release and salt crystallisation.

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

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

- The most effective salts are sodium sulphate, magnesium sulphate and calcium chloride.
- Chalk decomposes fastest, followed by limestone, sandstone and shale.
- The rate of disintegration of rocks is closely related to porosity and permeability.
- Surface texture and grain size control the rate of rock breakdown. This diminishes with time for fine materials and increases over time for coarse materials.
- Salt crystallisation is more effective than insolation weathering, hydration or freeze–thaw. However, a combination of freeze–thaw and salt crystallisation produces the highest rates of breakdown.

Heating and cooling may cause disintegration in hot desert areas where there is a large diurnal temperature range. In many desert areas, daytime temperatures exceed 40 °C, whereas night-time ones are little above freezing. Rocks heat up by day and contract by night. As rock is a poor conductor of heat, stresses occur only in the outer layers. This causes peeling or exfoliation to occur. Griggs (1936) showed that moisture is essential for this to happen. In the absence of moisture, temperature change alone did not cause the rocks to break down. The role of salt in insolation weathering has also been studied.

The expansion of many salts such as sodium, calcium, potassium and magnesium has been linked with exfoliation. However, some geographers find little evidence to support this view.

Pressure release (dilatation) is the process whereby overlying rocks are removed by erosion. This causes underlying rocks to expand and fracture parallel to the surface. The removal of a great weight, such as a glacier, has the same effect. Rocks are formed at very high pressure in confined spaces in the Earth's interior. The **unloading** of pressure by the removal of overlying rocks causes cracks or joints to form at right-angles to the unloading surface. These cracks are lines of weakness within the rock. For example, if overlying pressure is released, horizontal **pseudo-bedding planes** will be formed. By contrast, if horizontal pressure is released, as on a cliff face, vertical joints will develop. The size and spacing of cracks varies with distance from the surface: with increasing depth, the cracks become smaller and further apart. Hence the part of the rock that is broken the most is the part that is most subjected to denudation processes, namely at the surface.

Vegetation roots may also physically break down rocks. Figure 3.11 shows the impact of plants roots helping to break up rock.

Figure 3.11 Biological weathering – the physical impact of plant roots

Section 3.2 Activities

1. Define mechanical weathering.
2. Explain how freeze–thaw weathering operates.
3. Comment on the resistance to weathering (Table 3.2) compared with the pressure exerted by ice when it expands.
4. Describe the process of heating/cooling. Explain why it is common in hot, arid environments.

Chemical weathering

Water is the key medium for chemical weathering. Unlike mechanical weathering, chemical weathering is most effective sub-surface since percolating water has gained organic acids from the soil and vegetation. Acidic water helps to break down rocks such as chalk, limestone and granite. The amount of water is important as it removes weathered products by solution. Most weathering therefore takes place above the water table, since weathered material accumulates in the water and saturates it. There are three main types of chemical weathering: carbonation-solution, hydrolysis and hydration.

Carbonation-solution occurs on rocks with calcium carbonate, such as chalk and limestone. Rainfall combines with dissolved carbon dioxide or organic acid to form a weak carbonic acid.

$CO_2 + H_2O \leftrightarrow H_2CO_3$ (carbonic acid)

Calcium carbonate (calcite) reacts with an acid water and forms **calcium bicarbonate** (also termed 'calcium hydrogen carbonate'), which is soluble and removed by percolating water:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$$

calcite + carbonic acid → calcium bicarbonate

The effectiveness of solution is related to the pH of the water. For example, iron is highly soluble when the pH is 4.5 or less, and alumina (Al_2O_3) is highly soluble below 4.0 or above 9.0 but not in between.

Hydrolysis occurs on rocks with orthoclase feldspar, notably granite. Feldspar reacts with acid water and forms **kaolin** (also termed 'kaolinite' or 'china clay'), silicic acid and potassium hydroxyl:

$$2KAlSi_3O_8 + 2\,H_2O \rightarrow Al_2Si_2O_5\,(OH)_4 + K_2O + 4\,SiO_2$$

orthoclase feldspar + water → kaolinite + potassium hydroxyl + silicic acid

The acid and hydroxyl are removed in the solution, leaving kaolin behind as the end product. Other minerals in the granite, such as quartz and mica, remain in the kaolin. Hydrolysis also involves solution as the potassium hydroxyl is carbonated and removed in solution.

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

Section 3.2 Activities

1. Compare the character of rocks affected by mechanical weathering with those affected by chemical weathering.
2. Briefly explain the processes of carbonation-solution and hydrolysis.

Controls of weathering

The following factors affect the type and rate of weathering that takes place.

Climate

In the simplest terms, the type and rate of weathering vary with climate (Figure 3.12), but it is very difficult to isolate the exact relationship, at any scale, between climate type and rate of process. Peltier's diagrams (1950) show how weathering is related to moisture availability and average annual temperature (Figure 3.13; see also Table 3.3). In general, frost-shattering increases as the number of freeze–thaw cycles increases. By contrast, chemical weathering increases with moisture and heat. According to **Van't Hoff's Law**, the rate of chemical weathering increases 2–3 times for every increase in temperature of 10 °C (up to a maximum temperature of 60 °C). The efficiency of freeze–thaw, salt crystallisation and insolation weathering is influenced by:

- critical temperature changes
- frequency of cycles
- diurnal and seasonal variations in temperature.

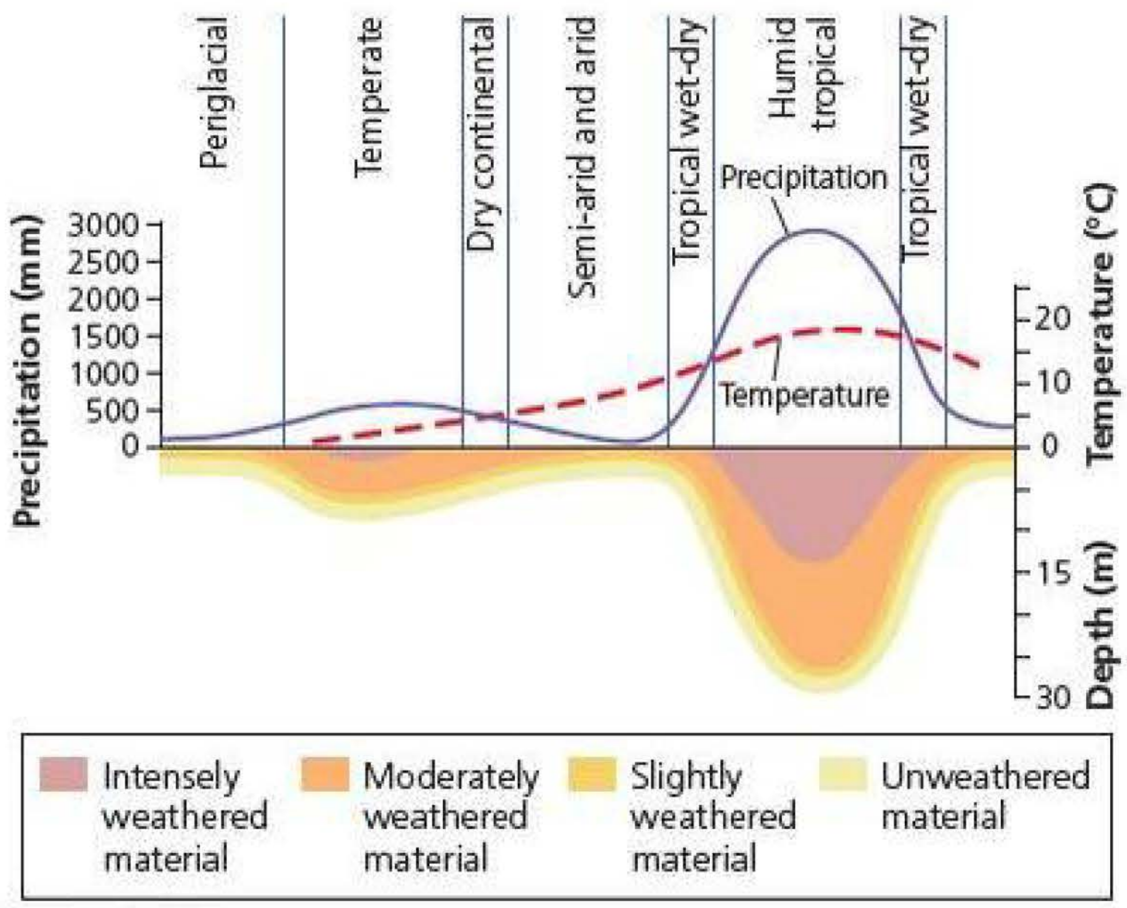


Figure 3.12 Depth of weathering profile and climate

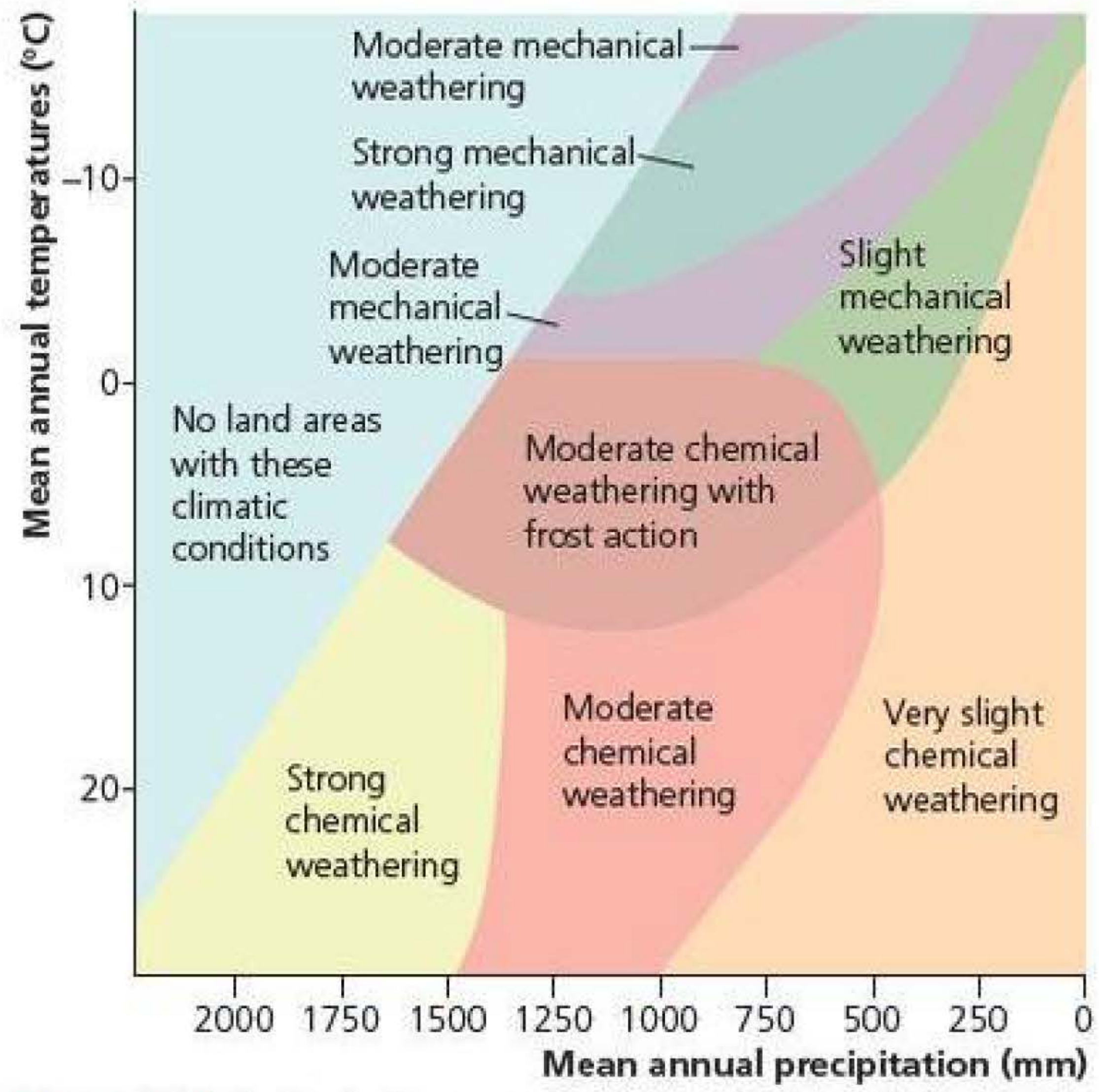


Figure 3.13 Peltier's diagram showing variations of chemical and mechanical weathering with climate

Table 3.3 Generalised weathering characteristics in four climatic regions

Climatic region	Characteristics	Examples – rates of weathering (mm yr^{-1})
Glacial/ Periglacial	Frost very important. Susceptibility to frost increases with increasing grain size. **Taiga:** fairly high soil leaching, low rates organic matter decomposition. **Tundra:** low precipitation, low temperatures, permafrost – moist conditions, slow organic production and breakdown. May have slower chemical weathering. Algal, fungal, bacterial weathering may occur. Granular disintegration occurs. Hydrolytic action reduced on sandstone, quartzite, clay, calcareous shales, phyllites, dolerites. Hydration weathering common due to high moisture. CO_2 is more soluble at low temperatures.	Narvik 0.001 Spitzbergen 0.02–0.2 Alaska 0.04
Temperate	Precipitation and evaporation generally fluctuate. Both mechanical weathering and chemical weathering occur. Iron oxides leached and redeposited. Carbonates deposited in drier areas, leached in wetter areas. Increased precipitation, lower temperatures, reduced evaporation. Organic content moderate to high, breakdown moderate. Silicate clays formed and altered. **Deciduous forest areas:** abundant bases, high nutrient status, biological activity moderate to high. **Coniferous areas:** acidic, low biological activity, leaching common.	Askrigg 0.5–1.6 Austria 0.015–0.04
Arid/semi-arid	Evaporation exceeds precipitation. Rainfall low. Temperatures high, seasonal. Organic content low. Mechanical weathering, salt weathering, granular disintegration, dominant in driest areas. Thermal effects possible. Low organic input relative to decomposition. Slight leaching produces $CaCO_3$ in soil. Sulphates and chlorides may accumulate in driest areas. Increased precipitation and decreased evaporation toward semi-arid areas and steppes yield thick organic layers, moderate leaching and $CaCO_3$ accumulation.	Egypt 0.0001–2.0 Australia 0.6–1.0
Humid tropical	High rainfall often seasonal. Long periods of high temperatures. Moisture availability high. Weathering products **a** removed or **b** accumulate to yield red and black clay soils, ferruginous and aluminous soils (lateritic), calcium-rich soils. Calcareous rocks generally heavily leached where silica content is high, soluble weathering products removed and parent silica in stable products are sandy. Where products remain, iron and aluminium are common. Usually intense deep weathering, iron and alumina oxides and hydroxides predominate. Organic content high but decomposition high.	Florida 0.005

Rock type

Rock type influences the rate and type of weathering in many ways due to:

- chemical composition
- the nature of cements in sedimentary rock
- joints and bedding planes.

For example, limestone consists of calcium carbonate and is therefore susceptible to carbonation-solution. By contrast, granite is prone to hydrolysis because of the presence of feldspar. In sedimentary rocks, the nature of the cement is crucial. Iron-oxide based cements are prone to oxidation, whereas quartz cements are very resistant.

Rock structure

The effect of rock structure varies from large-scale folding and faulting to localised patterns of joints and bedding planes. Joint patterns exert a strong control on water movement. These act as lines of weakness, thereby creating **differential resistance** within the same rock type. Similarly, grain size influences the speed with which rocks weather. Coarse-grained rocks weather quickly owing to a large void space and high permeability (Table 3.4). On the other hand, fine-grained rocks offer a greater surface area for weathering and may be highly susceptible to weathering. The importance of individual minerals was stressed by Goldich in 1938. Rocks formed of resistant minerals, such as quartz, muscovite and feldspar in granite, will resist weathering (Figure 3.14). By contrast, rocks formed of weaker minerals will weather rapidly. The interrelationship of geology and climate on the development of landforms is well illustrated by limestone and granite.

Table 3.4 Average porosity and permeability for common rock types

Rock type	Porosity (%)	Relative permeability
Granite	1	1
Basalt	1	1
Shale	18	5
Sandstone	18	500
Limestone	10	30
Clay	45	10
Silt	40	–
Sand	35	1100
Gravel	25	10000

Source: D. Brunsden, 'Weathering processes' in C. Embleton and J. Thornes (eds), Processes in Geomorphology, *Edward Arnold 1979*

Stability	Dark-coloured minerals	Light-coloured minerals	Susceptibility
Least stable	Olivine		Most susceptible
		Lime plagioclase	
	Augite		
		Lime soda plagioclase	
	Hornblende	Soda lime plagioclase	
		Soda plagioclase	
	Biotite		
Most stable	Orthoclase	Muscovite Quartz	Least susceptible

Figure 3.14 Goldich's weathering system

Vegetation

The influence of vegetation is linked with the type of climate and the nature of the soil. Moisture content, root depth and acidity of humus will influence the nature and rate of weathering. Vegetation weathers rocks in two main ways: through the secretion of organic acids, it helps to chemically weather the soil; and through the growth of roots, it physically weathers the soil.

Depth of soil may have an effect on the amount of weathering that occurs. Soils may protect rocks from further breakdown – or they may increase the rate of breakdown due to the vegetation it supports.

Relief

For weathering to continue, weathered material needs to be removed. If the slope is too shallow, removal might not occur. If the slope is too steep, water may flow over the surface. Hence, intermediate slope angles may produce most weathering.

Aspect is also important, as there may be important temperature differences between south- and north-facing slopes. However, this is important only if the temperature differences are around a critical temperature, for example 0°C for freeze–thaw weathering.

Section 3.2 Activities

1. a Define the terms *porosity* and *permeability*.
   b Choose a suitable method to show the relationship between porosity and permeability.
   c Describe the relationship between porosity and permeability.
   d What are the exceptions, if any, to this relationship?
2. Describe and explain how the type and intensity of mechanical weathering varies with climate.
3. Describe and explain how the type and intensity of chemical weathering varies with climate.
4. How useful are mean annual temperature and mean annual rainfall as a means of explaining variations in the type and intensity of weathering processes?
5. Describe two ways in which vegetation affects the type and rate of weathering.

3.3 Slope processes

Introduction and definitions

The term 'slope' refers to:

- an inclined surface or hillslope
- an angle of inclination or slope angle.

Slopes therefore include any part of the solid land surface, including level surfaces of 0° (Figure 3.15). These can be sub-aerial (exposed) or sub-marine (underwater), aggradational (depositional), degradational (erosional), transportational or any mixture of these. Given the large scope of this definition, geographers generally study the hillslope. This is the area between the watershed (or drainage-basin divide) and the base. It may or may not contain a river or stream.

Slope processes

Many slopes vary with climate. In humid areas, slopes are frequently rounder, due to chemical weathering, soil creep and fluvial transport. By contrast, in arid regions slopes are jagged or straight owing to mechanical weathering and sheetwash (Figure 3.16). Climatic geomorphology is a branch of geography that studies how different processes operate in different climatic zones, and produce different slope forms or shapes (see Table 3.3 in Section 3.2).

Geological structure is another important control on slope development. This includes faults, angle of dip and vulcanicity. These factors influence the strength of a rock and create lines of potential weakness within it. In addition, rock type and character affect vulnerability to weathering and the degree of resistance to downslope movement.

Geological structure can also influence the occurrence of landslips. Slopes composed of many different types of rock are often more vulnerable to landslides due to differential erosion; that is, less resistant rocks are worn away and can lead to the undermining of more resistant rocks.

Figure 3.15 Rounded slopes at Wytham, Oxfordshire, UK – a temperate region

Figure 3.16 Silent Valley, Dolomites, Italy

Soil can be considered as part of the regolith. Its structure and texture will largely determine how much water it can hold. Clay soils can hold more water than sandy soils. A deep clay on a slope where vegetation has been removed will offer very little resistance to mass movement.

Aspect refers to the direction in which a slope faces. In some areas, past climatic conditions varied depending on the direction a slope faced. During the cold periglacial period in the northern hemisphere, in an east–west valley, the southern slope which faced north, remained in the shade. Temperatures rarely rose above freezing. By contrast, the northern slope, facing south, was subjected to many more cycles of freeze–thaw. Solifluction and overland runoff lowered the level of the slope, and streams removed the debris from the valley. The result was an asymmetric valley.

Vegetation can decrease overland runoff through the interception and storage of moisture. Deforested slopes are frequently exposed to intense erosion and gullying. However, vegetation can also increase the chance of major landslips. Dense forests reduce surface wash, causing a build-up of soil between the trees, thus deepening the regolith and increasing the potential for failure.

Section 3.3 Activities

1. Briefly describe **two** ways in which climate affects slope development. What does the term *climatic geomorphology* mean?
2. Briefly describe **two** ways in which geology affects slope development.

Mass movements

Mass movements include any large-scale movement of the Earth's surface that are not accompanied by a moving agent such as a river, glacier or ocean wave. They include:

- **very slow movements**, such as soil creep
- **fast movement**, such as avalanches
- **dry movement**, such as rockfalls
- **very fluid movements**, such as mudflows (Figure 3.17).

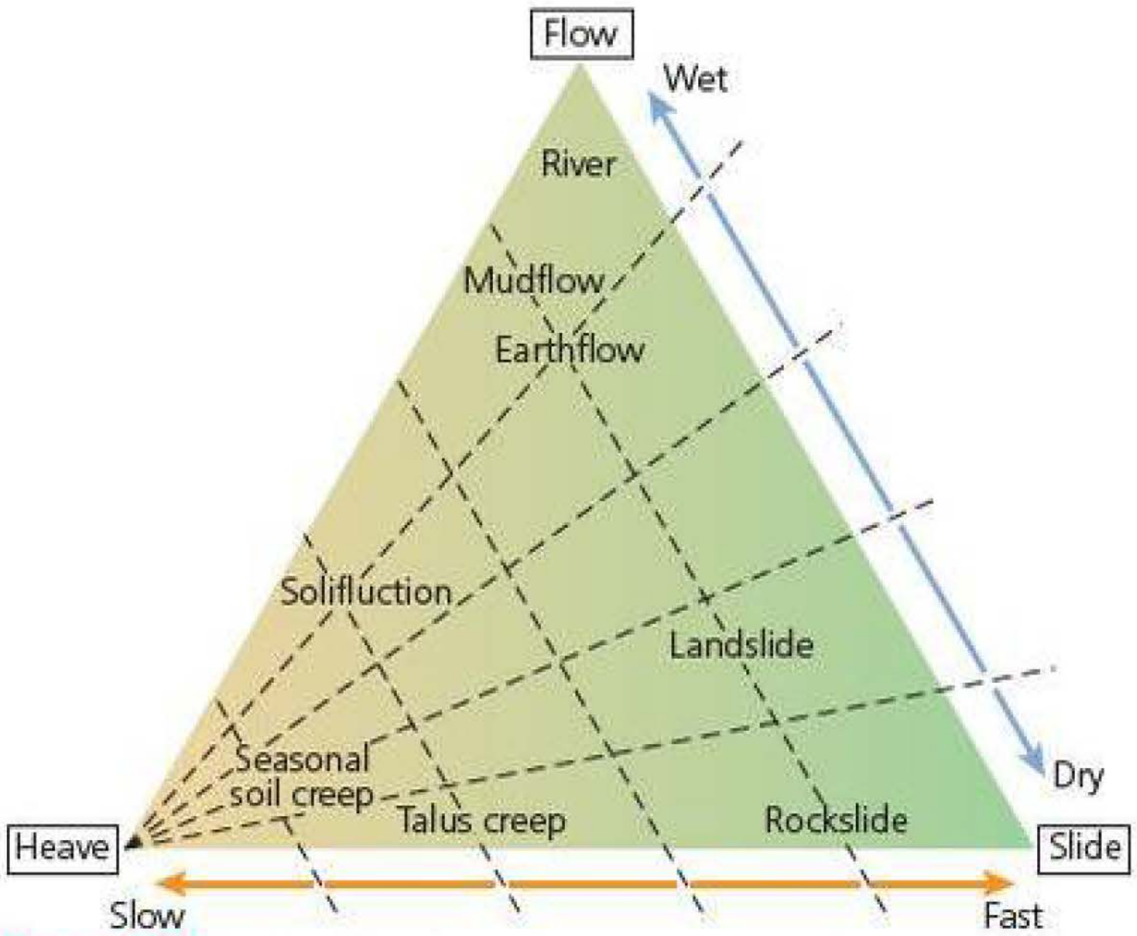


Figure 3.17 A classification of mass movements

A range of slope processes occur that vary in terms of magnitude, frequency and scale. Some are large and occur infrequently, notably rockfalls, whereas others are smaller and more continuous, such as soil creep.

The types of processes can be classified in a number of different ways:

- speed of movement (Figure 3.18)
- water content
- type of movement: flows, slides, slumps
- material.

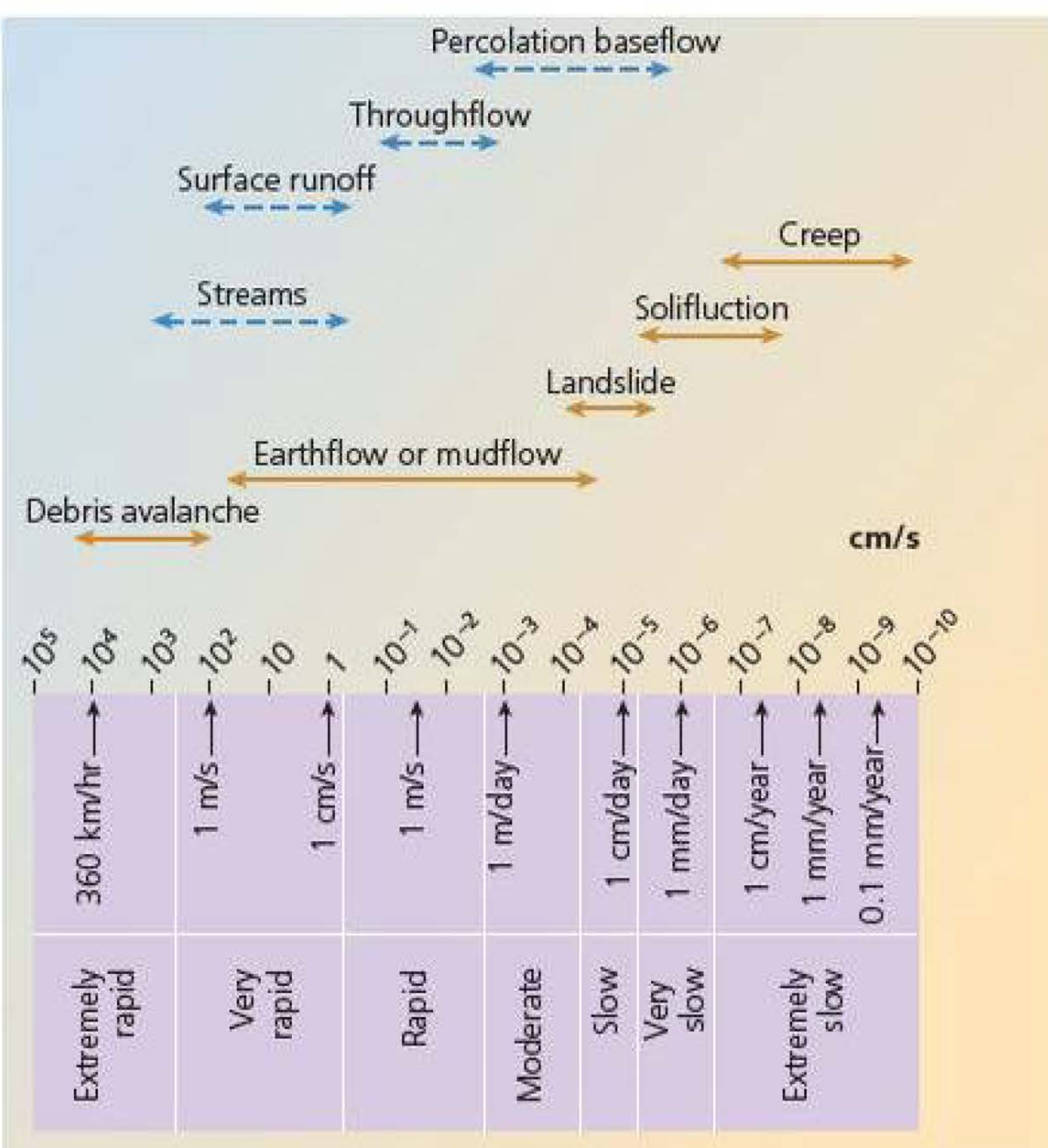


Figure 3.18 Speed of mass movements

Causes of mass movements

The likelihood of a slope failing can be expressed by its safety factor. This is the relative strength or resistance of the slope, compared with the force that is trying to move it. The most important factors that determine movement are gravity, slope angle and pore pressure.

Gravity has two effects. First, it acts to move the material downslope (a slide component). Second, it acts to stick the particle to the slope (a stick component). The downslope movement is proportional to the weight of the particle and slope angle. Water lubricates particles and in some cases fills the spaces between the particles. This forces them apart under pressure. Pore pressure will greatly increase the ability of the material to move. This factor is of particular importance in movements of wet material on low-angle slopes.

Shear strength and shear resistance

Slope failure is caused by two factors:

1. a reduction in the internal resistance, or shear strength, of the slope, or
2. an increase in shear stress; that is, the forces attempting to pull a mass downslope.

Both can occur at the same time.

Increases in shear stress can be caused by a multitude of factors (Table 3.5). These include material

Table 3.5 Increasing stress and decreasing resistance

Factor	Example
Factors that contribute to increased shear stress	
Removal of lateral support through undercutting or slope steepening	Erosion by rivers and glaciers, wave action, faulting, previous rockfalls or slides
Removal of underlying support	Undercutting by rivers and waves, subsurface solution, loss of strength by extrusion of underlying sediments
Loading of slope	Weight of water, vegetation, accumulation of debris
Lateral pressure	Water in cracks, freezing in cracks, swelling (especially through hydration of clays), pressure release
Transient stresses	Earthquakes, movement of trees in wind
Factors that contribute to reduced shear strength	
Weathering effects	Disintegration of granular rocks, hydration of clay minerals, dissolution of cementing minerals in rock or soil
Changes in pore-water pressure	Saturation, softening of material
Changes of structure	Creation of fissures in shales and clays, remoulding of sand and sensitive clays
Organic effects	Burrowing of animals, decay of tree roots

characteristics, weathering processes and changes in water availability. Weaknesses in rocks include joints, bedding planes and faults. Stress may be increased by:

- steepening or undercutting of a slope
- addition of a mass of regolith
- dumping of mining waste
- sliding from higher up the slope
- vibrational shock
- earthquakes.

Weathering may reduce cohesion and resistance. Consequently, material may be more susceptible to movement on slopes, even though the original material was stable.

Water can weaken a slope by increasing shear stress and decreasing shear resistance. The weight of a potentially mobile mass is increased by:

- an increase in the volume of water
- heavy or prolonged rain
- a rising water table
- saturated surface layers.

Moreover, water reduces the cohesion of particles by saturation. Water pressure in saturated soils (pore-water pressure) decreases the frictional strength of the solid material. This weakens the slope. Over time the safety factor for a particular slope will change. These changes may be gradual, for example percolation carrying away finer material. By contrast, some changes are rapid.

There are a number of ways that downslope movement can be opposed:

- **Friction** will vary with the weight of the particle and slope angle. Friction can be overcome on gentle slope angles if water is present. For example, solifluction can occur on slopes as gentle as 3°.
- Cohesive forces act to bind the particles on the slope. Clay may have high cohesion, but this may be reduced if the water content becomes so high that the clay liquefies, when it loses its cohesive strength.
- Pivoting occurs in the debris layers which contain material embedded in the slope.
- **Vegetation** binds the soil and thereby stabilises slopes. However, vegetation may allow soil moisture to build up and make landslides more likely (see pages 75–77).

Section 3.3 Activities

1 a Define the term *mass movement*.
  b Suggest how mass movements can be classified.
2 Define the terms *strength* and *shear stress*.
3 With the use of examples, explain why mass movements occur.

Types of mass movement

Heave or creep is a slow, small-scale process that occurs mostly in winter. It is one of the most important slope processes in environments where flows and slides are not common. Talus creep is the slow movement of fragments on a scree slope.

Individual soil particles are pushed or heaved to the surface by **a** wetting, **b** heating or **c** freezing of water (Figure 3.19). About 75 per cent of the soil-creep movement is induced by moisture changes and associated volume change. Nevertheless, freeze–thaw and normal temperature-controlled expansion and contraction are important in periglacial and tropical climates.

Particles move at right-angles to the surface (2) as it is the zone of least resistance. They fall under the influence of gravity (5) once the particles have dried, cooled, or the water has thawed. Next movement is downslope.

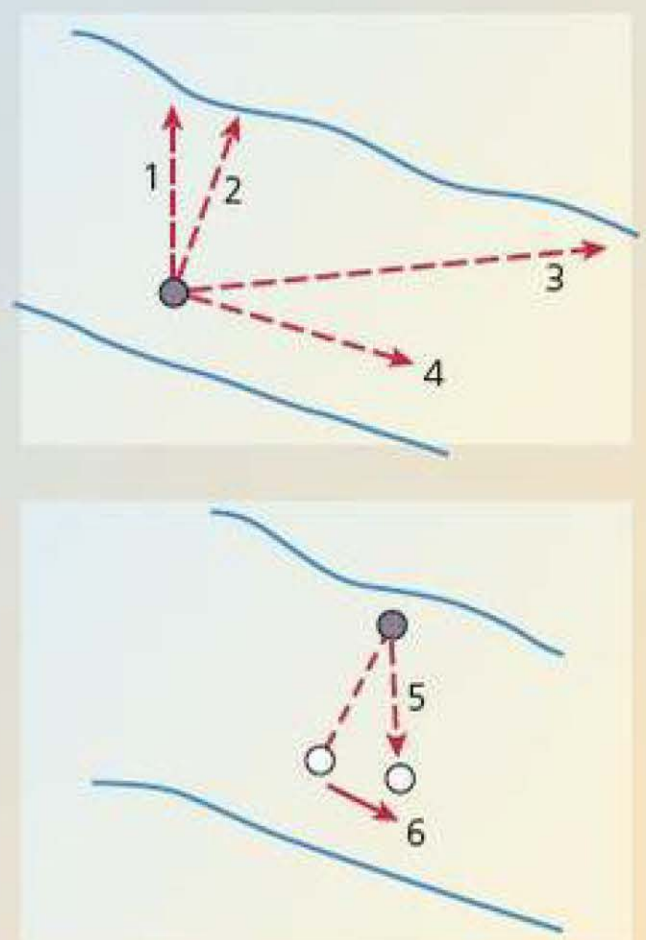


Figure 3.19 Soil creep

Rates of soil creep are slow, at 1–3 millimetres per year in temperate areas and up to 10 millimetres per year in tropical rainforest. They form terracettes. In well-vegetated humid temperate areas, soil creep can be ten times more important than slope wash. In periglacial areas, it can be as much as 300 millimetres per year. By contrast, in arid environments slope wash is more important. Small-scale variations in slope, compaction, cohesion and vegetation will have a significant effect on the rate of creep.

Observation of soil creep is difficult. Traditional qualitative evidence such as bent trees (Figure 3.20) is misleading and now largely discredited. The slow rate of movement may mean that measurement errors are serious.

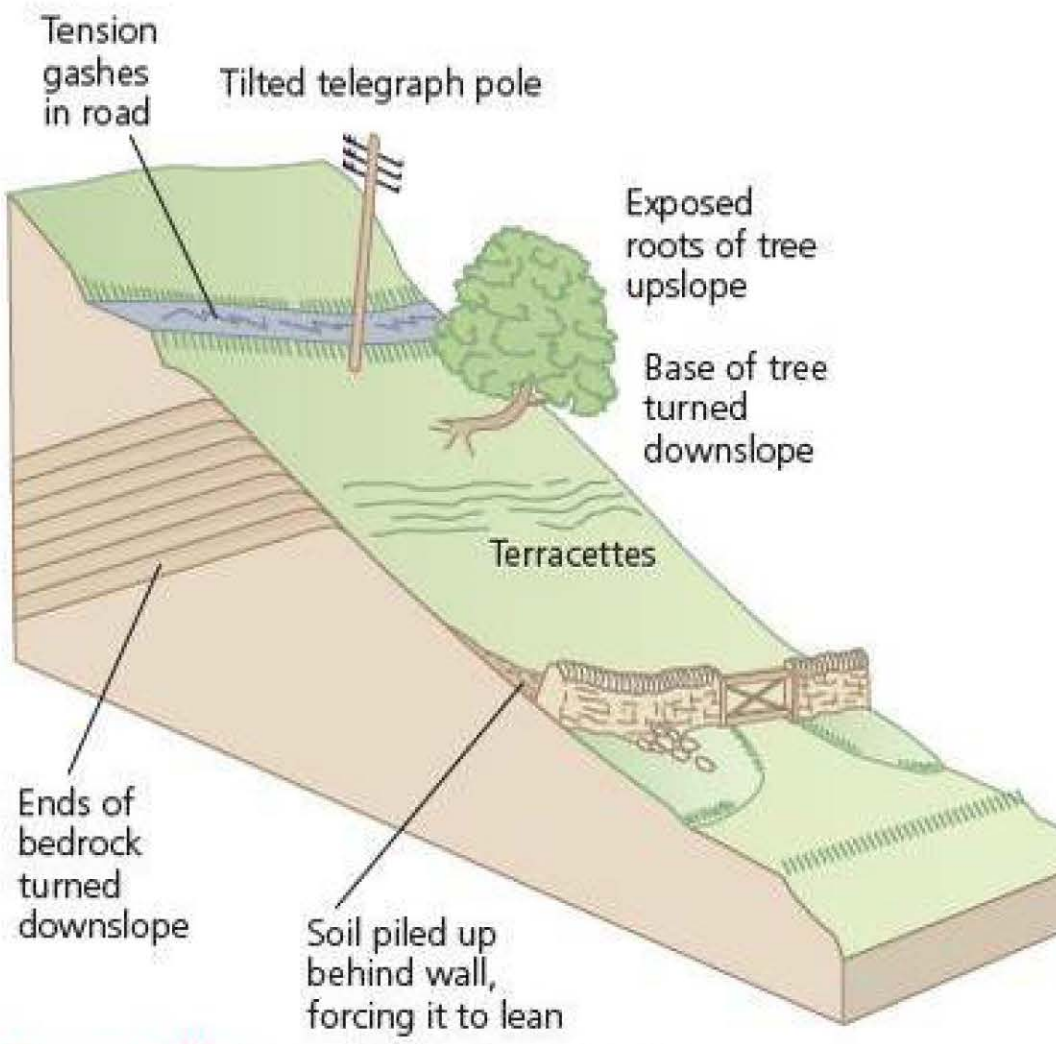


Figure 3.20 The evidence for soil creep

Slumps and flows

Slumps occur on weaker rocks, especially clay, and have a rotational movement along a curved slip plane (Figure 3.21). Clay absorbs water, becomes saturated and exceeds its liquid limit. It then flows along a slip plane. Frequently the base of a cliff has been undercut and weakened by erosion, thereby reducing its strength. By contrast, flows are more continuous, less jerky, and are more likely to contort the mass into a new form (Figure 3.22). Material is predominantly of a small size, such as deeply weathered clays. Particle size involved in flows is generally small, for example sand-sized and smaller.

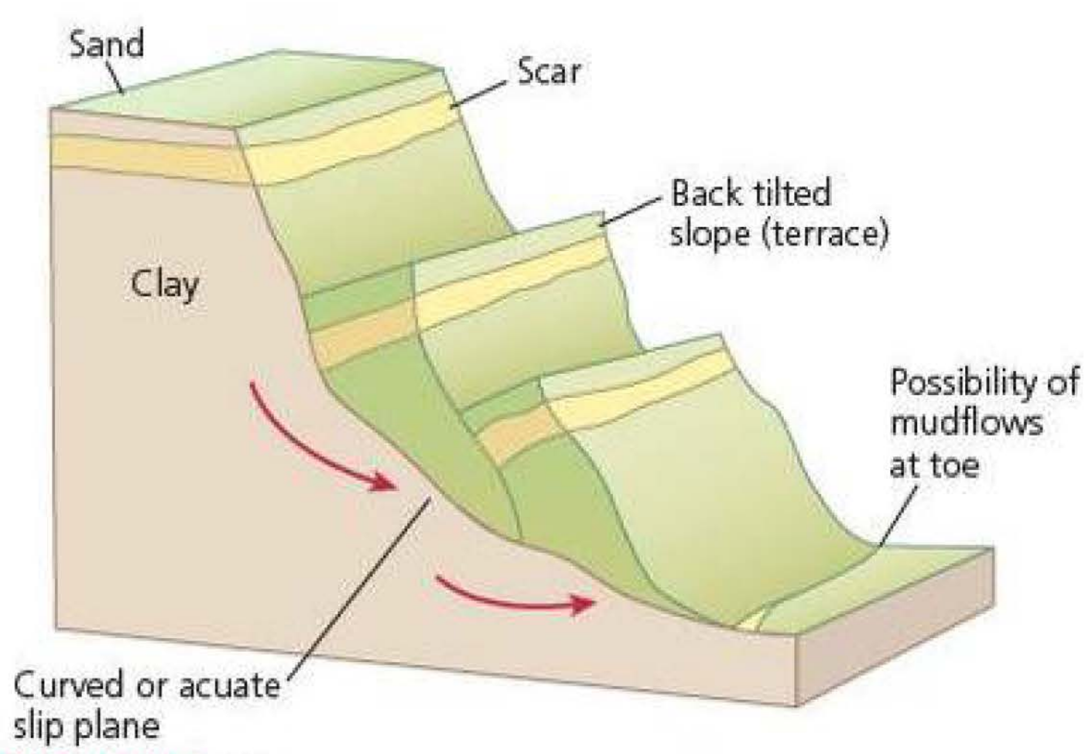


Figure 3.21 Slumps

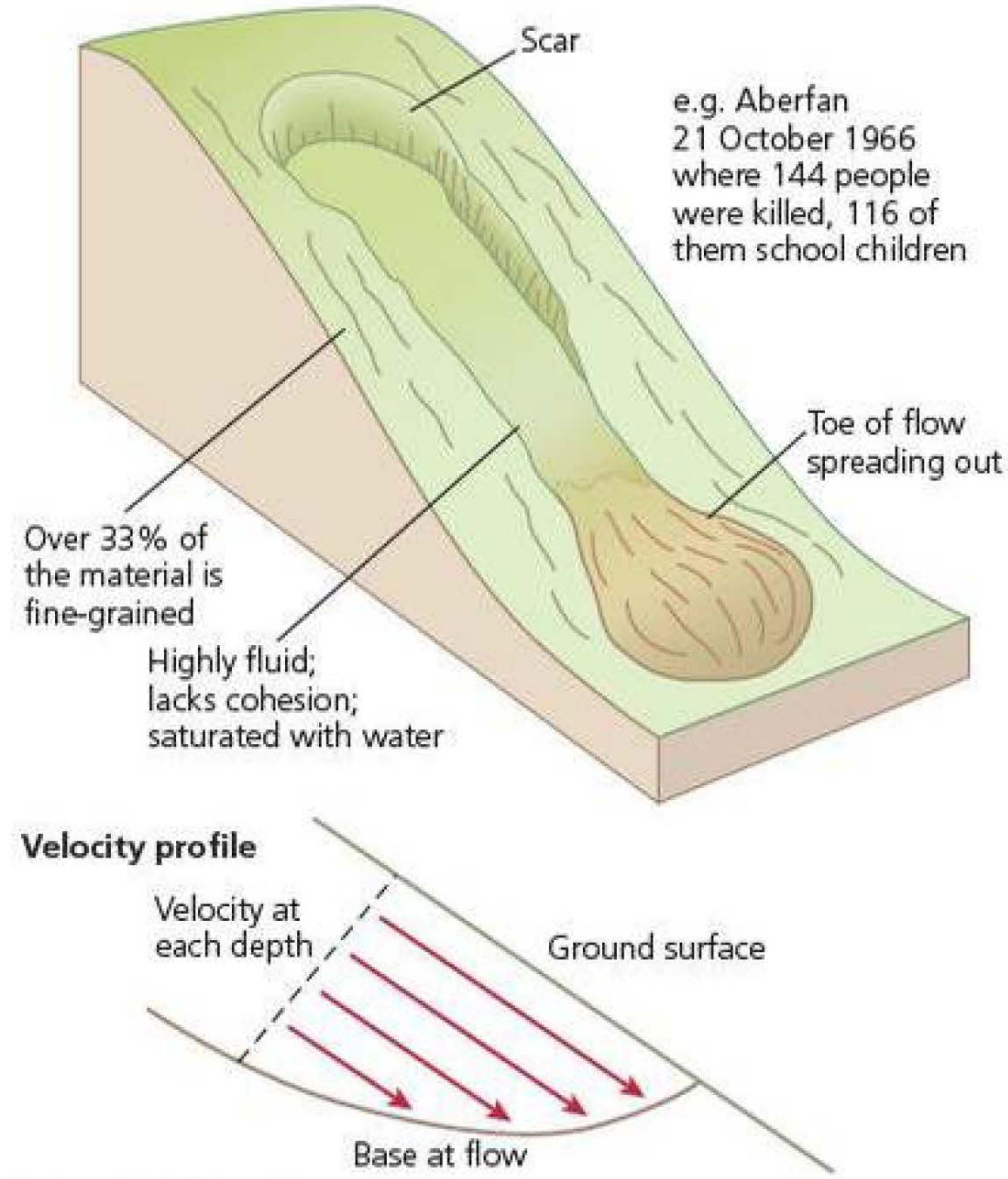


Figure 3.22 Flows

The speed of a flow varies: mudflows are faster and more fluid than earthflows, which tend to be thicker and deeper. A higher water content will enable material to flow across gentle angles.

Earthflows and mudflows can occur on the saturated toe (end) of a landslide, or may form a distinctive type of mass movement in their own right. Small flows may develop locally, whereas others may be larger and more rapid. In theory, mudflows give way to sediment-laden rivers – but the distinction is very blurred.

Case Study: Sidoarjo mudflow

Since May 2006, more than 50 000 people in Porong District, Indonesia, have been displaced by hot mud flowing from a natural well. Gas and hot mud began spewing out when a drill penetrated a layer of liquid sediment. The amount of material spilling out peaked at 135 000 m^3/day in September 2006. By 2010, the main thoroughfare in Porong was raised 80 cm to avoid further mudflows. The Sidoarjo mudflow is an ongoing eruption of gas and mud.

Slides

Slides occur when an entire mass of material moves along a slip plane. These include:

- **rockslides and landslides** of any material, rock or regolith
- **rotational slides**, which produce a series of massive steps or terraces.

Slides commonly occur where there is a combination of weak rocks, steep slopes and active undercutting. Slides are often caused by a change in the water content of a slope or by very cold conditions. As the mass moves along the slip plane, it tends to retain its shape and structure until it hits the bottom of a slope (Figure 3.23). Slides range from small-scale slides close to roads, to large-scale movements that kill thousands of people.

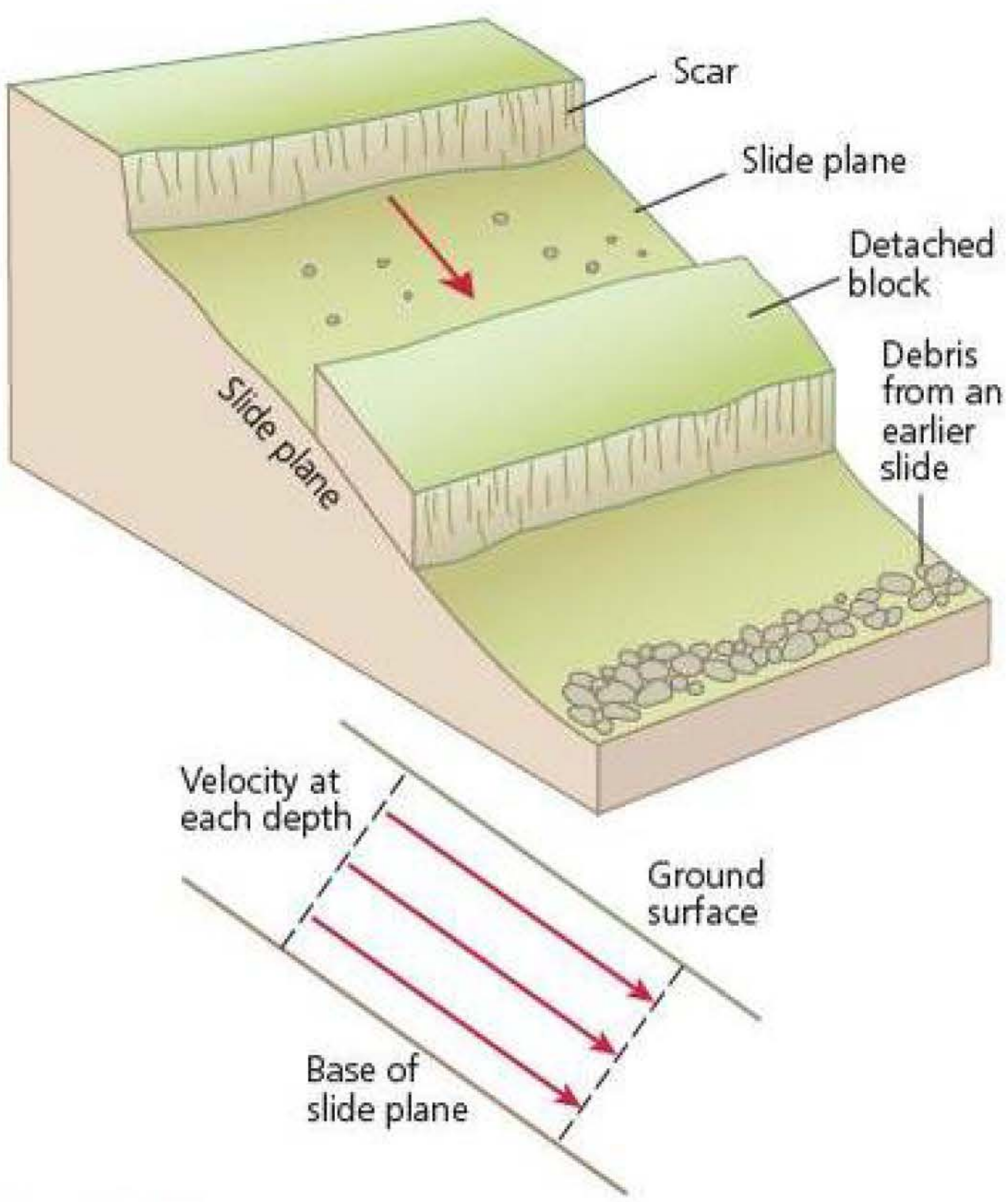


Figure 3.23 Slides

Slip planes occur for a variety of reasons:

- at the junction of two layers
- at a fault line
- where there is a joint
- along a bedding plane
- at the point beneath the surface where the shear stress becomes greater than the shear strength.

Weak rocks such as clay have little shear strength to start with, and are particularly vulnerable to the development of slip planes. The slip plane is typically a concave curve and as the slide occurs the mass will be rotated backwards.

Rockslides

In 1959, the sixth strongest earthquake ever to affect the USA occurred in Montana. Close to the epicentre of the earthquake, in the Madison River valley, a slope of schists and gneiss with slippery mica and clay was supported by a base of dolomite. The earthquake cleanly broke the dolomite. A huge volume of rock, 400 metres high and 1000 metres long, slid into the valley; 80 million tonnes of material moved in less than a minute! The Madison River was dammed and a lake 60 metres deep and 8 kilometres long was created.

Landslides

Loose rock, stones and soil all have a tendency to move downslope. They will do so whenever the downward force exceeds the resistance produced by friction and cohesion. When the material moves downslope as a result of shear failure at the boundary of the moving mass, the term 'landslide' is applied. This may include a flowing movement as well as straightforward sliding. Landslides are very sensitive to water content, which reduces the strength of the material by increasing the water pressure. This effectively pushes particles apart, thereby weakening the links between them. Moreover, water adds weight to the mass, increasing the downslope force.

Case Study: The Abbotsford landslide, Dunedin, New Zealand

The landslide that took place in East Abbotsford, South Island, New Zealand is a very good example of how human and physical factors can interact to produce a hazardous event. It also shows clearly how such hazards can be managed.

From 1978, several families in Abbotsford noticed hairline cracks appearing in their homes – in the brickwork, concrete floors and driveways. During 1979, workmen discovered that a leaking water main had been pulled apart. Geologists discovered that water had made layers of clay on the hill soft, and the sandstone above it was sliding on this slippery surface.

As a result, an early warning system was put in place. A civil defence emergency was declared on 6 August, although the situation wasn't thought to be urgent as geologists believed that landslip would continue to move only slowly. However, on 8 August a 7 hectare section of Abbotsford started down the hill at a rate of over 3 metres a minute (Figure 3.24), with houses and 17 people on board. No-one was killed, although 69 homes were destroyed or damaged and over 200 people were displaced. The total cost from the destruction of the homes, infrastructure and relief operation amounted to over £7 million. An insurance scheme designed to cope with such disasters, and government and voluntary relief measures, meant that many of the residents were compensated for their loss. However, other costs, such as depressed house prices in the surrounding area, psychological trauma and the expense of a prolonged public enquiry, were not immediately appreciated.

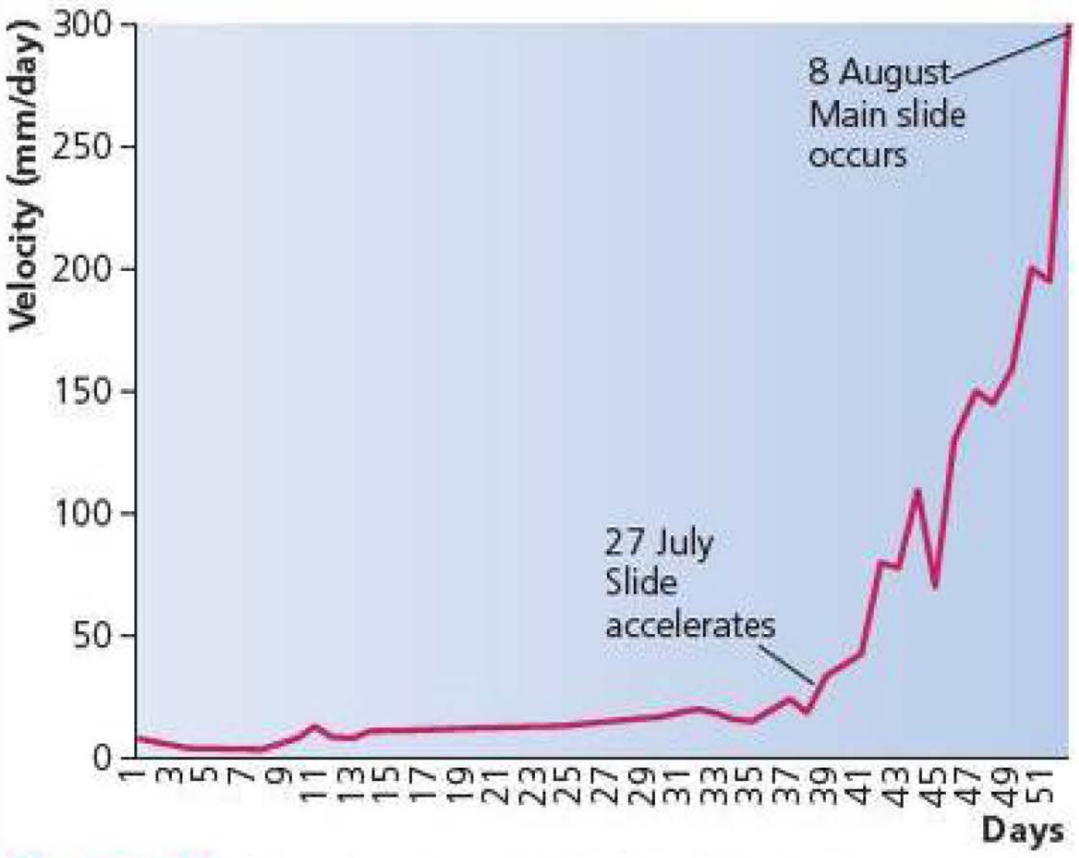


Figure 3.24 Abbotsford landslide, New Zealand

The landslide was essentially a block slide of sandstone resting on a bed of weaker clay. Displacement of 50 metres took place in about 30 minutes, leaving a small rift 30 metres deep at the head of the slope. Such geological conditions – in which a permeable hard rock rests on an impermeable soft rock – are commonly associated with landslides. In addition, the slope was dipping at an angle of 7°. Water collected in the impermeable clay, reduced its strength and cohesion, and caused the sandstone to slip along the boundary of the two rocks.

The landslide involved 5.4 million m^3 of material. At first, the land moved as a slow creep, followed by a rapid movement with speeds of 1.7 metres per minute. Rapid sliding lasted for about 30 minutes. An area of about 18 hectares was affected.

However, other factors are also believed to have made a contribution. Deforestation in the area, even over a century before, had reduced evapotranspiration in the area and there was less binding of the soil by plant roots. Urbanisation in the previous 40 years had modified the slopes by cutting and infilling, and had altered surface drainage (speeding up the removal of surface water). Quarrying of material at the toe of the slope in the 1960s and 1970s had removed support from the base of the slope. The trigger of the landslide is believed to have been a combination of leaking water pipes and heavy rainfall.

A number of lessons can be learnt from the Abbotsford landslide:

- Dangerous landslides can occur on relatively gentle slopes if the right conditions exist.
- Attention to early warning can help preparedness and reduce the loss of life.
- Human activity can destabilise slopes.
- Low-frequency, high-magnitude events may be hard to predict, but mapping and dating of old hazards may indicate areas of potential risk – a regional landslide **hazard assessment** should be made where there is evidence of previous landslide activity.
- A landslide insurance scheme eased the cost of the event – however, money was available only after the event rather than beforehand, and the insurance only covered houses, not land damage.

Section 3.3 Activities

1. What were the causes of the Abbotsford landslide?
2. Describe the impacts of the Abbotsford landslide.
3. What lessons can be learnt from the Abbotsford landslide?

Case Study: Mexican landslides, 2010

In October 2010, mud buried part of a remote town in the southern Mexican state of Oaxaca when a large chunk of a nearby mountain collapsed after three days of relentless rain. Initially, it was thought that the landslide had caused a massive tragedy with up to 1000 people killed. However, the number of deaths was believed to be less than ten. The landslide happened at about four o'clock in the morning. The authorities were unsure how many houses had been buried because it was dark, so they estimated.

The rescue progress along the unpaved mountain road was hampered by smaller landslides and a collapsed bridge. Heavy cloud cover prohibited helicopters from getting a clear view of the situation on the ground. When the first rescue workers and soldiers eventually reached the town, they found considerable destruction in one relatively small part of the town. Two houses were completely interred, two partially buried and thirty more in serious danger because they lay within the path of the still-unstable mudflow.

In 2010, Mexico experienced one of the most intense rainy seasons on record, with large areas under water in lowland regions of Oaxaca as well as in other southern states. Landslides are a major danger in mountainous parts of the country – particularly those, such as Oaxaca, that have long suffered from severe deforestation.

Falls

Falls occur on steep slopes (greater than 40°), especially on bare rock faces where joints are exposed. The initial cause of the fall may be weathering, such as freeze–thaw or disintegration, or erosion prising open lines of weakness. Once the rocks are detached, they fall under the influence of gravity (Figure 3.25). If the fall is short, it produces a relatively straight scree. If it is long, it forms a concave scree. Falls are significant in producing the retreat of steep rock faces and in providing debris for scree slopes and talus slopes.

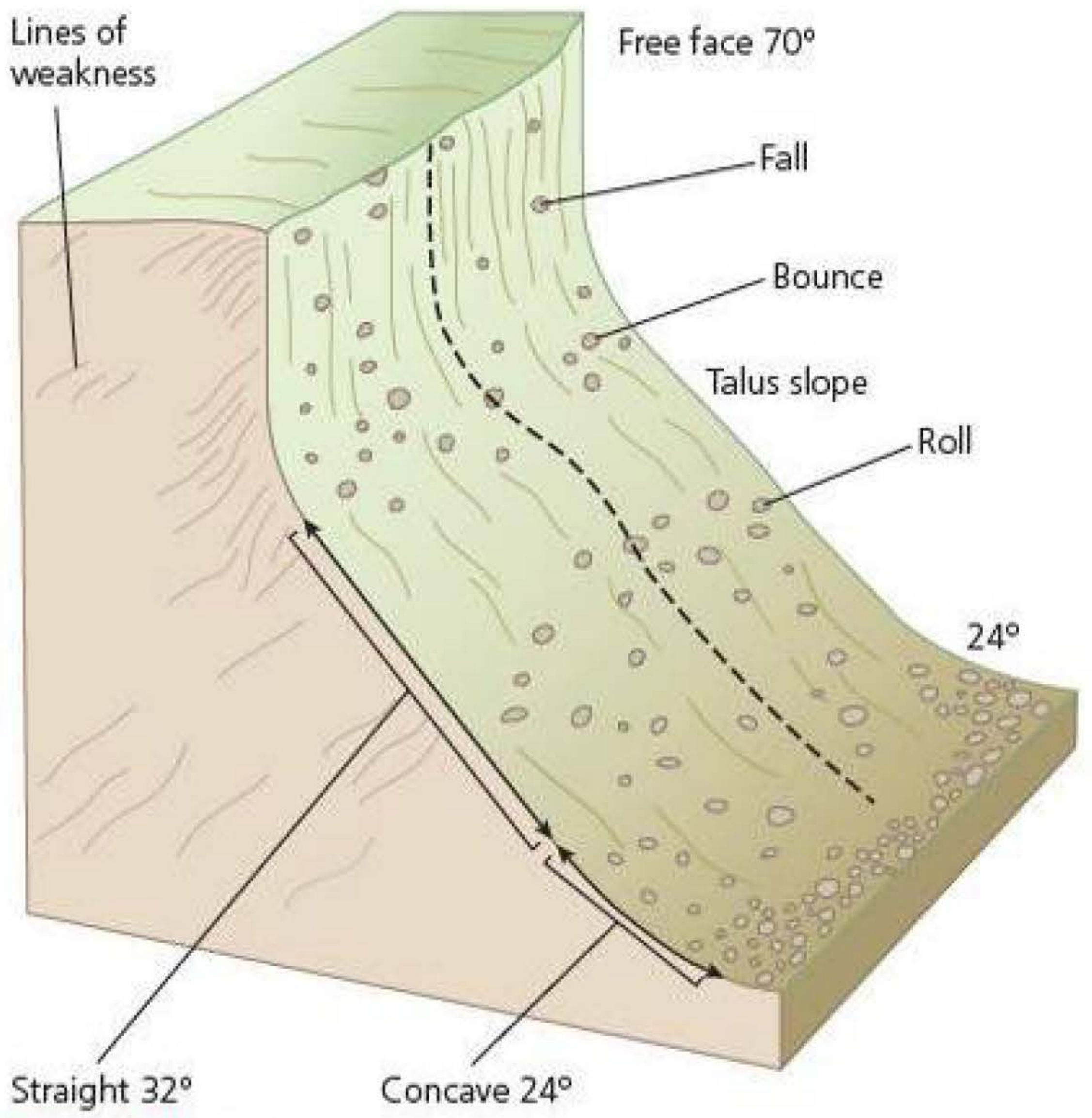


Figure 3.25 Falls

Section 3.3 Activities

1 Explain the terms *mass movement*, *soil creep* and *rotational slide*.
2 Outline the main characteristics of slumps and flows.

Water and sediment movement on hillslopes

Surface wash occurs when the soil's infiltration capacity is exceeded. In the UK, this commonly occurs in winter as water drains across saturated or frozen ground, following prolonged or heavy downpours or the melting of snow. It is also common in arid and semi-arid regions where particle size limits percolation.

Sheetwash is the unchannelled flow of water over a soil surface. On most slopes, sheetwash breaks into areas of high velocity separated by areas of lower velocity. It is capable of transporting material dislodged by rainsplash (see the following section). Sheetwash occurs in the UK on footpaths and moorlands. For example, during the Lynmouth floods of 1952, sheetwash from the shallow moorland peat caused gullies 6 metres deep to form. In the semi-arid areas of south-west USA, it lowers surfaces by 2–5 millimetres per year compared with 0.01 millimetres per year on vegetated slopes in a temperate climate.

Sheetwash erosion of soil occurs through raindrop impact and subsequent transport by water flowing overland rather than in channels. The result is a relatively uniform layer of soil being eroded. A **rill** is a relatively shallow channel, generally less than tens of centimetres deep and carrying water and sediment for only a short period. Rills are common in agricultural areas, following the removal of vegetation during the harvest season, and the ground subsequently being left bare. They are also common in areas following deforestation or land-use changes. Ground compaction by machinery may also lead to the generation of rills during rainfall events.

Throughflow refers to water moving down through the soil. It is channelled into natural pipes in the soil. This gives it sufficient energy to transport material, and added to its solute load, may amount to a considerable volume.

Rainsplash erosion

Raindrops can have an erosive effect on hillslopes (Figure 3.26). On a 5° slope, about 60 per cent of the movement is downslope. This figure increases to 95 per cent on a 25° slope. The amount of erosion depends on the rainfall intensity, velocity and raindrop distribution. It is most effective on slopes of between 33° and 45° and at the start of a rainfall event when the soil is still loose.

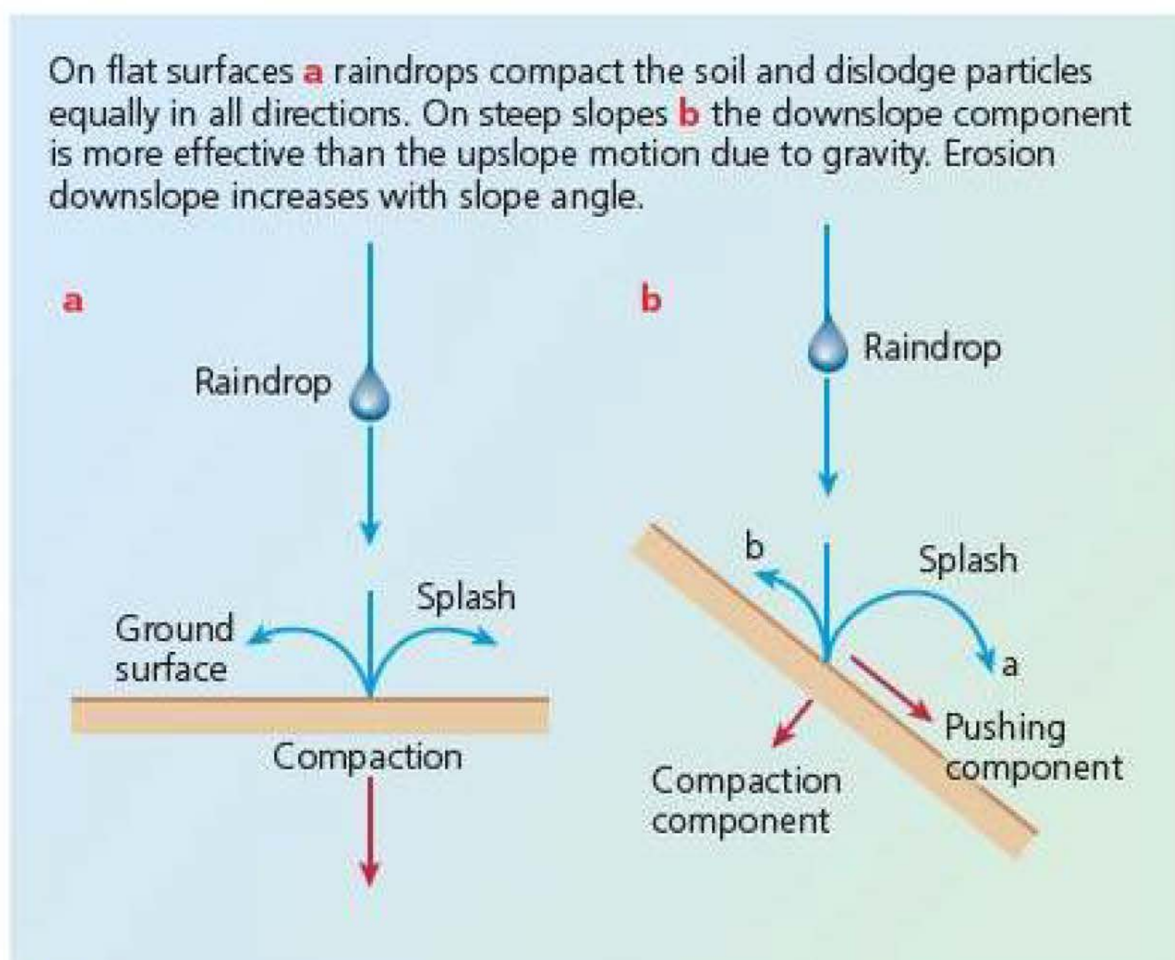


Figure 3.26 Rainsplash erosion

Section 3.3 Activities

1 Briefly explain how rainsplash erosion occurs.
2 Define the term *sheetwash*.
3 Under what conditions do rills occur?

3.4 The human impact

Stability of slopes

Rates of mass movement can be altered by human activities, such as building or excavation, drainage or agriculture. Mass movements can be accelerated by destabilising slopes. Local erosion can be intensified by footpath trampling in recreational areas. Some mass movements are created by humans piling up waste soil and rock into unstable accumulations that move without warning. Landslides can be created by undercutting or overloading. Most changes to slopes caused by human activities have been very minor in relation to the scale of the natural land surface. Human interference with slopes tends to have been most effective in speeding up naturally occurring processes rather than creating new features.

In urban areas, the intensity of slope modification is often very high, given the need for buildings and roads to be constructed safely, using sound engineering principles. Almost all buildings with foundations cause some modification to the natural slope of the land, and even on flat sites, large modern buildings generally involve the removal of material to allow for proper foundations. Slope modification tends to increase as a construction moves on to steeper slopes. In these conditions, in order to provide a horizontal base plus reasonable access, a cut-and-fill technique is often used (Figure 3.27), thereby creating a small level terrace with an over-steepened slope at both ends. The steep slopes, devoid of soil and vegetation, are potentially much less stable than the former natural slope and are, in times of intense rainfall, susceptible to small but quite damaging landslips.

Strategies to reduce mass movement

As well as causing mass movements, human activities can reduce them (Table 3.6).

Table 3.6 Examples of methods of controlling mass movement

Type of movement	Method of control
Falls	Flattening the slope Benching the slope Drainage Reinforcement of rock walls by grouting with cement, anchor bolts Covering of wall with steel mesh
Slides and flows	Grading or benching to flatten the slope Drainage of surface water with ditches Sealing surface cracks to prevent infiltration Subsurface drainage Rock or earth buttresses at foot Retaining walls at foot Pilings through the potential slide mass

Source: Goudie, 1993

Pinning is used to attach wire nets (or sometimes concrete blocks) to a rock face or slope so that the risk of rock falls is reduced or the risk of erosion is reduced. **Netting** may help collect fragments of scree, which can be safely removed at a later date. This is often used in areas where tourism is important, and where the risk of rock fall is high.

Grading refers to the re-profiling of slopes (see Figure 3.27) so that they become more stable. Afforestation is the planting of new forest in upper parts of a catchment to increase interception and reduce overland flow. They may take many years to be effective as the young, immature trees intercept relatively small amounts of water.

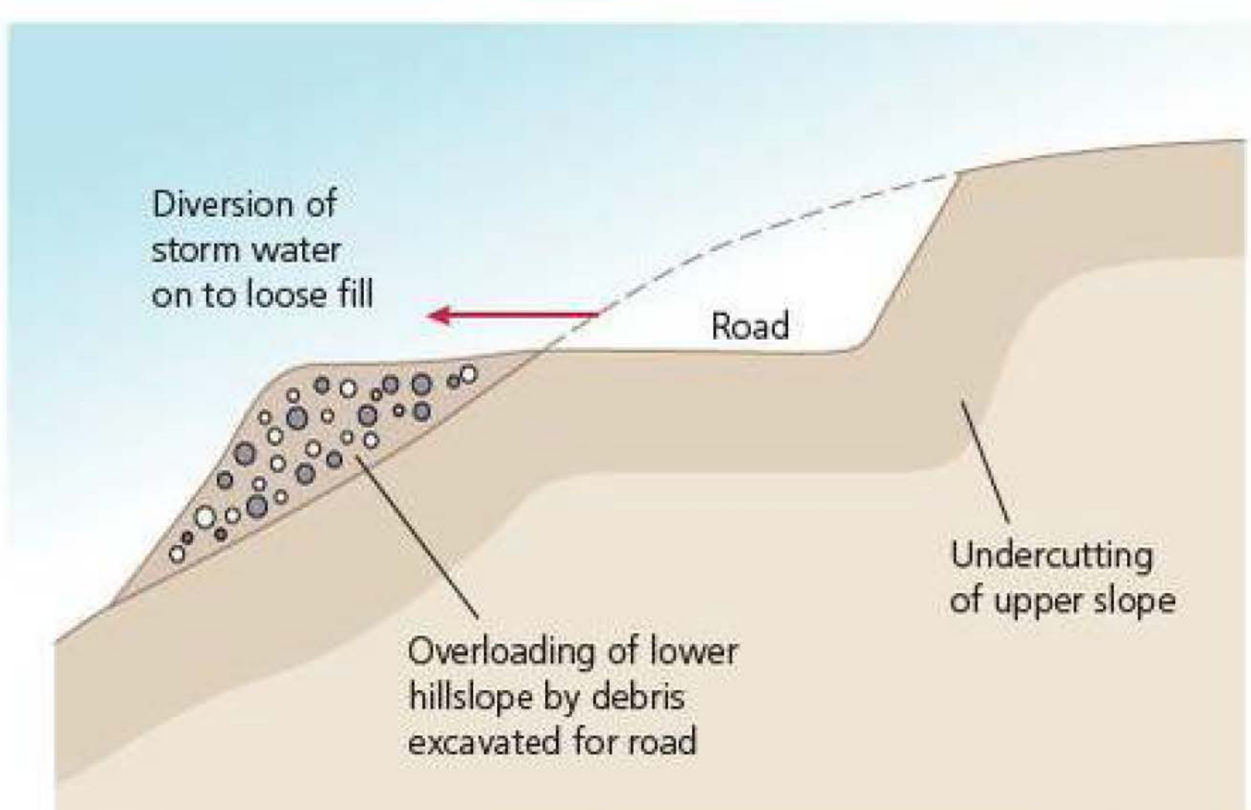


Figure 3.27 Slope instability caused by road building

Case Study: Landslides in Hong Kong

Hong Kong has a long history of landslides – largely due to a combination of high rainfall (the wet season is from May to September), steep slopes and dense human developments on the islands (Figure 3.28). Between 1947 and 1997, more than 470 people died as a result of landslides.

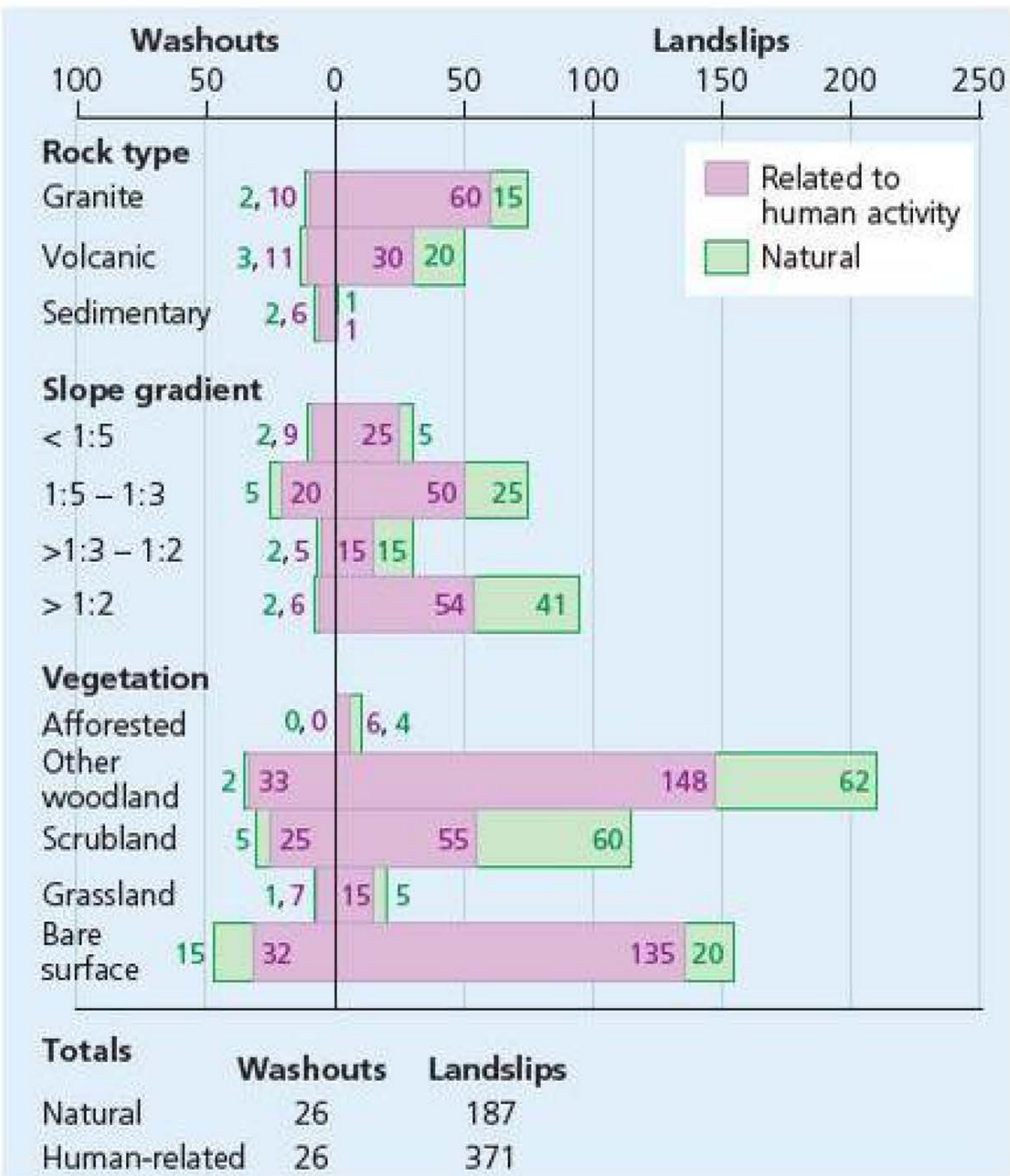


Figure 3.28 Number of mass movements per 100 km² in Hong Kong in the 1960s and 1970s

In June 1966, rainstorms triggered massive landslides that killed 64 people. Over 2500 people were made homeless and a further 8000 were evacuated. Rainfall had been high for the first ten days in June. Over 300 millimetres had fallen, compared with 130 millimetres in a normal year. On 11 and 12 June, over 400 millimetres fell – nearly a third of this occurred in just one hour! By 15 June, the area had received over 1650 millimetres of rain. Over 700 landslides were recorded in Hong Kong that month.

Some geographers believe that vegetation increased the problem. The trees held back many of the smaller landslides and allowed the larger ones, **washout**, to occur. Other forms of landslides included debris avalanches and rockslides.

At 1075 km², Hong Kong is one of the most densely populated urban areas worldwide, with a population of over 7 million (2015). It consists of the main island of Hong Kong, the peninsula of Kowloon, the New Territories and more than 230 islands with natural steep terrain and hills. The upper slopes are steeper than 30°. Most of the population is concentrated along the less steep urban areas on both sides of Victoria Harbour (Figure 3.30). With urban development, landslides are triggered by excavation and building works (Figures 3.31 and 3.32).

Figure 3.29 Hong Kong landscape

Figure 3.30 Map of Hong Kong showing Victoria Harbour

Figure 3.31 Landslide warning sign

Figure 3.32 Steep slopes and dense urban development combine to create a landslide risk

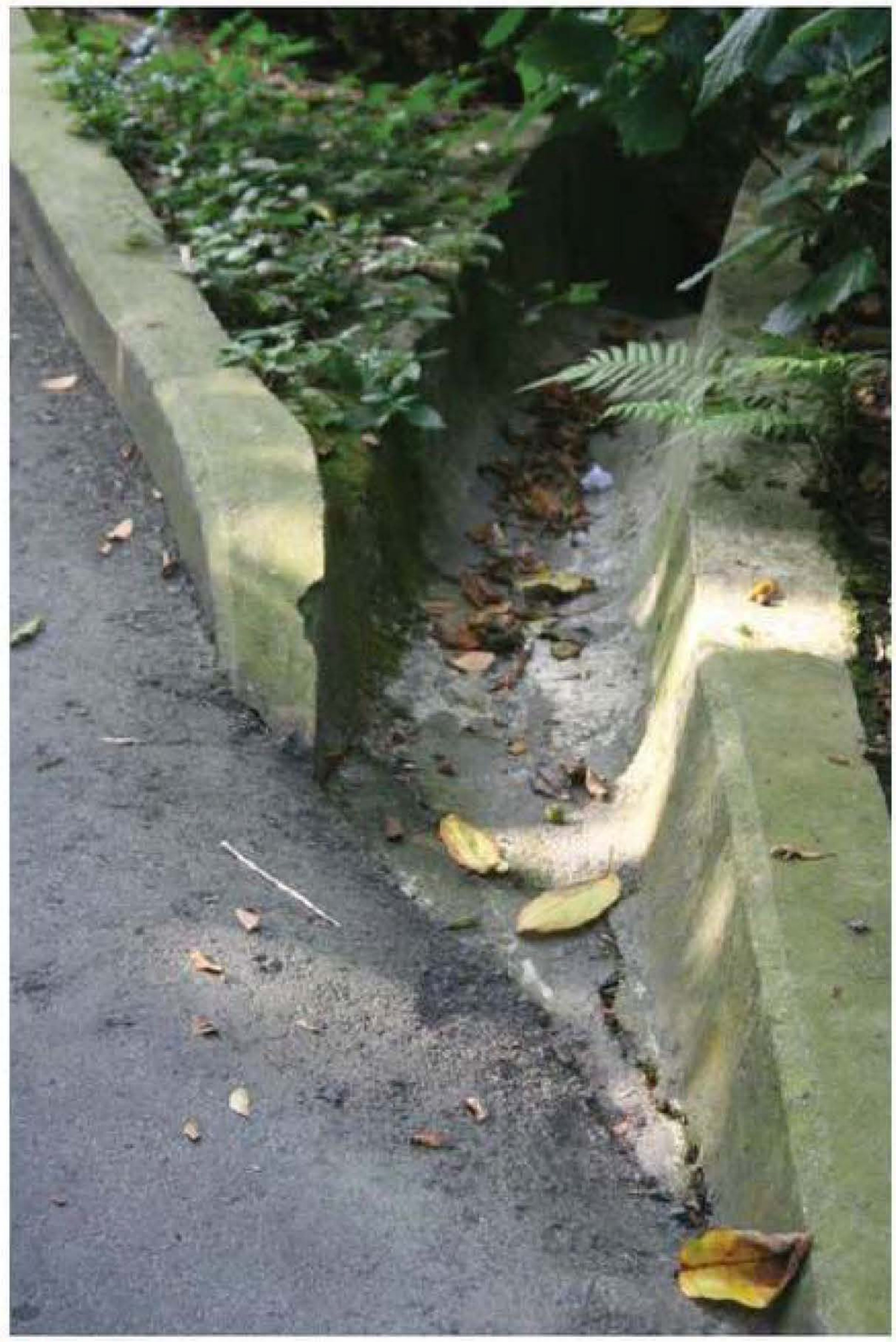


Figure 3.33 Drainage channel

Geology

The geology of Hong Kong is constructed mainly from three rock types: sedimentary rocks, granites and volcanic rocks. The sedimentary rocks generally form the lowlands. The granites and volcanic rocks, however, are situated on higher ground and are prone to failure. Both are seriously weathered, although granite rocks tend to be weathered more deeply than volcanic rocks. Volcanic rocks are more resilient and less prone to weathering and therefore less prone to slope failure.

Managing landslides in Hong Kong

The Hong Kong government has a responsibility to manage landslides. The Slope Safety System is managed by the Geotechnical Engineering Office (GEO) of the Civil Engineering Development Department (CEDD). The GEO has a staff establishment of over 700 for its wide range of activities. The GEO maintains its slope safety through investigating and researching the causes of significant and serious landslides to improve the Slope Safety Systems. The GEO is continuously updating, maintaining and disclosing the Catalogue of Slopes, which contains information of some 57 000 sizeable man-made slopes in Hong Kong.

One of Hong Kong's government interventions is to ensure that the private owners of slopes take responsibility for slope safety. If a slope owner does not comply with the regulation, prosecution will lead to a HK$50 000 fine, and to imprisonment for up to one year.

The government intervention in Hong Kong has had successful results. The risk from landslides has been reduced by 50 per cent since 1977. However, as a result of continued population growth, developers increasingly build further up the slopes. The risk from landslides, therefore, increases and the damages from a potential slide become greater.

Maintenance of slopes

Since heavy rainfall and surface runoffs are contributing to slope failure in Hong Kong, it is vital to remove excess water from slopes. Surface draining systems and protective covers are two methods used to protect slopes.

Surface drains are very vulnerable to blockage. Without proper drain maintenance, landslides are more common than on slopes without drains. Unfortunately, due to confusion over the responsibility, many drains are not properly maintained.

Man-made slopes are one of the main methods of slope stabilisation used in Hong Kong. These contain drains to intercept and direct water away from the slopes. The slope is usually protected from infiltration and the erosive effects of water by impermeable hard covers.

Greening techniques refer to the use of natural vegetation to reduce the risk of mass movements. There are three main types of greening techniques that are used in Hong Kong:

- The mulching system provides a protective cover that makes it possible for natural vegetation to grow on the slope; a natural vegetative cover is able to grow through the mat, securing it in place.
- The use of **long-rooting grass** is a fast and cost-effective system to cover man-made slopes. This system is applied by drilling planter holes into a hard cover. The drilled hole is then filled with soil mix and fertilisers, and finally the long-rooting grass is planted within.
- The **fibre reinforced soil system** is constructed by mixing polyester fibre into sandy soils. This mixture is capable of resisting tension.

Some of the advantages of greening techniques are outlined in Table 3.7.

Table 3.7 The advantages of greening techniques

Greening techniques	Advantages
Mulching system	Higher adhesive capacity on steep slopes High resistance to rain erosion High water-retaining capacity Long-lasting fertilisers Adaptable to rough surfaces
Planting long-rooting grass	Natural and environmentally friendly Cost-effective Fast and easy installation Can be applied on steep slopes Low maintenance
Fibre reinforced soil system	Self-sustained vegetation system with low maintenance Fibre strengthens soil particles to prevent erosion Visual improvement of the slope with various plant species Restoration of natural habitats on the slope

Section 3.4 Activities

1 Using the data in Table 3.8, draw a climate graph for Hong Kong. Describe the main characteristics of Hong Kong's climate.

Table 3.8 Climate data for Hong Kong

Month	Average temperature (°C)	Rainfall (mm)
January	16	30
February	15	60
March	18	70
April	22	133
May	25	332
June	28	479
July	28	286
August	28	415
September	27	364
October	25	33
November	21	46
December	17	17
Average/total	**23**	**2265**

2 Study Figure 3.28, which provides details of landslides in Hong Kong.
   a Using the data, describe and explain the relationship between mass movements and i rock type, ii gradient and iii vegetation.
   b What type of mass movement was most common in Hong Kong?
   c What do you think is the difference between a washout and a landslip? Give reasons for your answer.
   d Which type of rock was most affected by a washouts and b landslips?
   e What type of mass movement most affected a granite and b volcanic rocks? How do you explain these differences?
   f What is the relationship between gradient and mass movement? Give reasons for your answer.
   g What impact does vegetation have on the type and number of mass movements? Briefly explain your answer.
   h Briefly discuss the impact of human activity on mass movements. Use the evidence in Figure 3.28 to support your answer.

3 Study Figure 3.30, a map of Hong Kong. Using map evidence, suggest why landslides are a hazard in Hong Kong.

4 Suggest how population growth in Hong Kong contributes to the landslide hazard.

5 Describe the methods of landslide management that are used in Hong Kong.