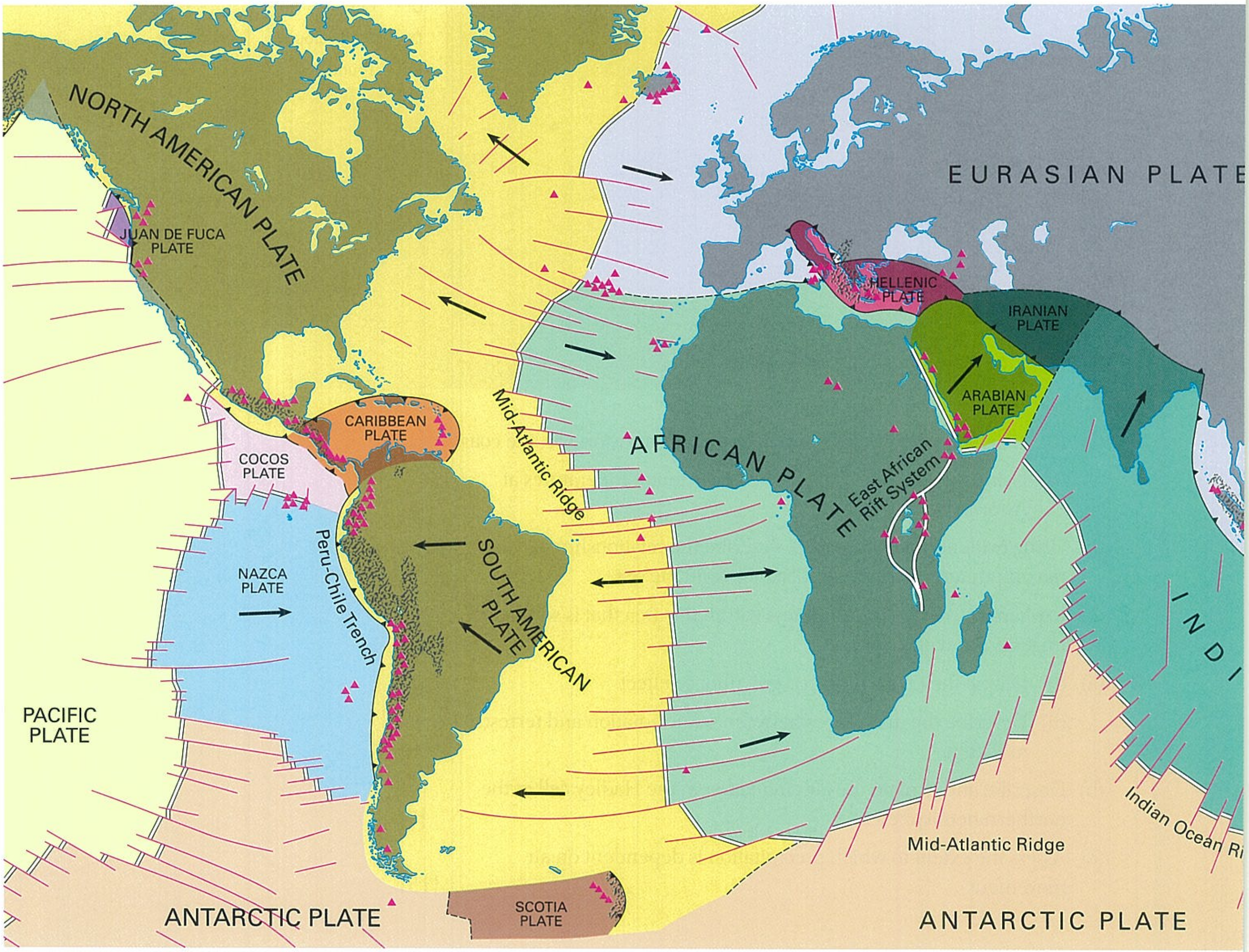
3 Rocks and weathering

In this chapter you will learn about:

- → The Earth's tectonic plates and how they link to major surface landforms such as fold mountains, ocean ridges, ocean trenches and volcanic island arcs.
- → The processes of weathering which break down surface rocks.
- → The processes acting on hill slopes and how they modify the landscape.
- → How slopes can become unstable and how people can respond to this.



Figs. 3.1 The world's tectonic plates

Plate tectonics

Global patterns of plates

The upper part of planet Earth is known as the **lithosphere**. It is colder than the part of the Earth below it and therefore more rigid. The thickness of the lithosphere varies greatly, ranging from less than 15 kilometres for young oceanic lithosphere to about 200 kilometres or more for ancient continental lithosphere, e.g. the interior parts of North and South America. The average is 50-75 kilometres. The lithosphere includes the Earth's crust and part of the upper mantle. Below the lithosphere is the **asthenosphere**. The boundary between the two (the base of the lithosphere) is taken at the 1300 °C isotherm, dividing the colder, more rigid rocks above from the hotter, more plastic rocks below. There is no change in composition at this boundary.

The lithosphere is divided into a number of **plates** which move relative to one another. Some of the plates are large but there are also smaller plates.

The concept of **plate tectonics** - meaning that the lithospheric plates are in motion and that the movement is responsible for the formation of major landforms - was developed in the 1960s and 1970s. This was partly a result of the first surveys of the floors of the deep ocean basins. The idea of **continental drift** was proposed about 100 years ago but it was not completely accepted until the ocean floor evidence came to light and plate tectonic theory was developed.

1. Name the seven major plates and note whether they include part of an ocean, part of a continent, or both.

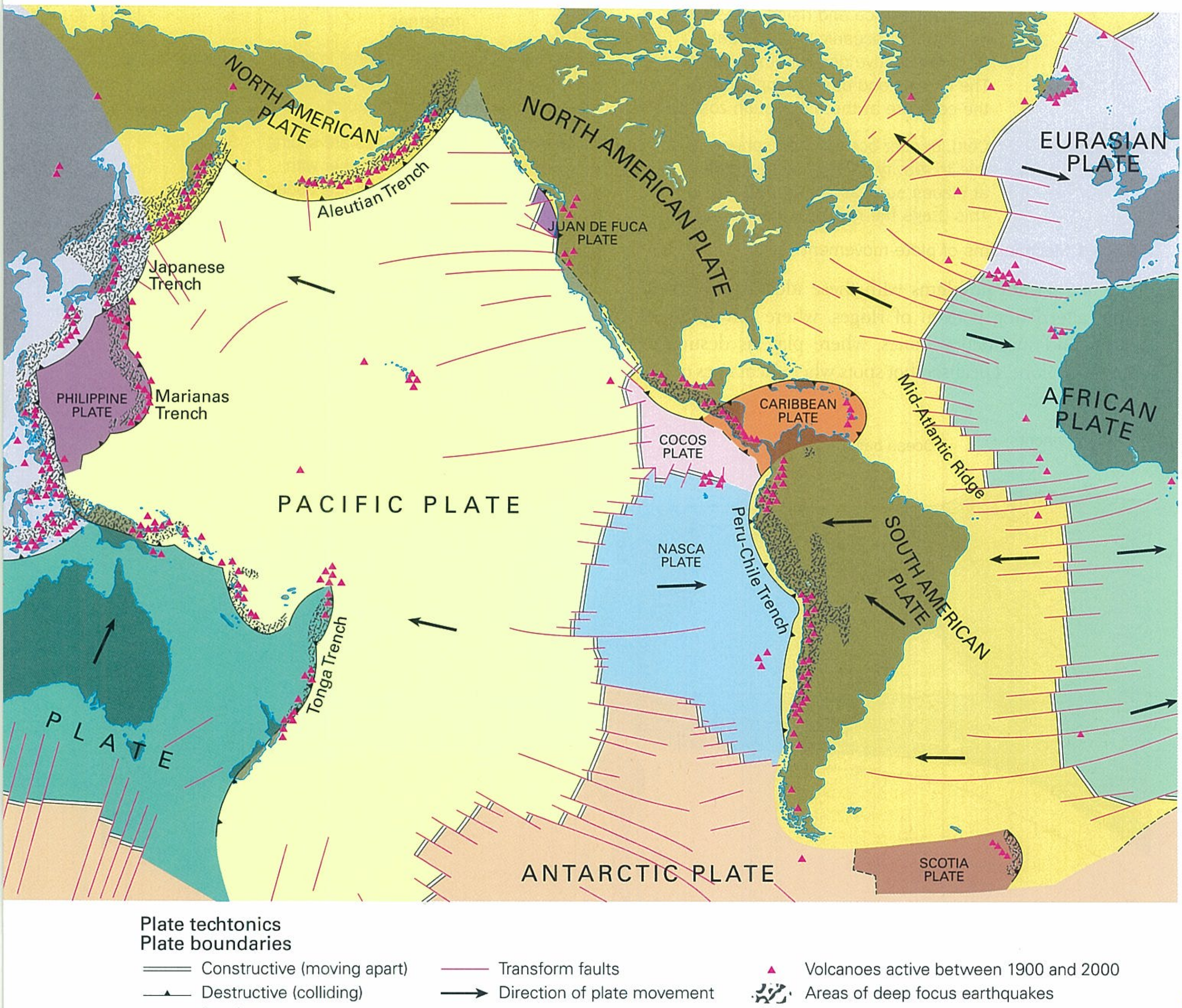


Plate movements

Measurements, taken using fixed stars as reference points, show that the plates are moving between 1 and 10 centimetres a year. Most of the ideas about these plate movements are related to convectional movements of material in the Earth's mantle. Deep within the Earth, heat is being produced by radioactivity. Some areas are hotter than others. At the hotter areas the plastic rocks in the Earth's mantle are thought to become lighter and rise, causing convection currents. This may involve the three mechanisms shown in Table 3.1.

Ridge push	Intrusion of magma into the spreading ocean ridges such as the Mid-Atlantic Ridge propels plates apart.
Convection drag	Convection currents in the plastic mantle drag the overlying lithosphere. The heat source and rising limbs are beneath the oceanic ridges. Heat is from radioactive decay in the mantle. The cooling and descending parts of the cells are at the subduction zones.
Slab pull	Cold, denser oceanic lithosphere sinks due to gravity into the subduction zones at places such as the Aleutian trench. This drags the rest of the plate with it.

Table 3.1 Mechanisms of plate movement

There are certain problems with these ideas. There is no simple alternating pattern of ridges, where new plate is created, and subduction zones, where plate is destroyed, around the globe. Localised hot spots where heat rises occur in places such as Hawaii, well away from the spreading ridges. The mantle may be too rigid to behave like a liquid and allow convection cells to develop.

Plate boundaries (plate margins)

The boundaries between the plates are belts of *major* earthquakes. There are three main types of plate margin, as shown in Table 3.2.

Type of boundary	Description	Type of stress affecting the area
Convergent (destructive)	Where material is being destroyed or subducted and the plates are moving together.	Compression → ←
Divergent (constructive)	Where material is being added and the plates are moving apart.	Tension ← →
Conservative	Where plates are sliding past one another with no material being added to or subducted from either side.	Shearing → ←
Collision	Where two continental plates meet and subduction has ceased	Compression → ←

Table 3.2 Types of plate margin

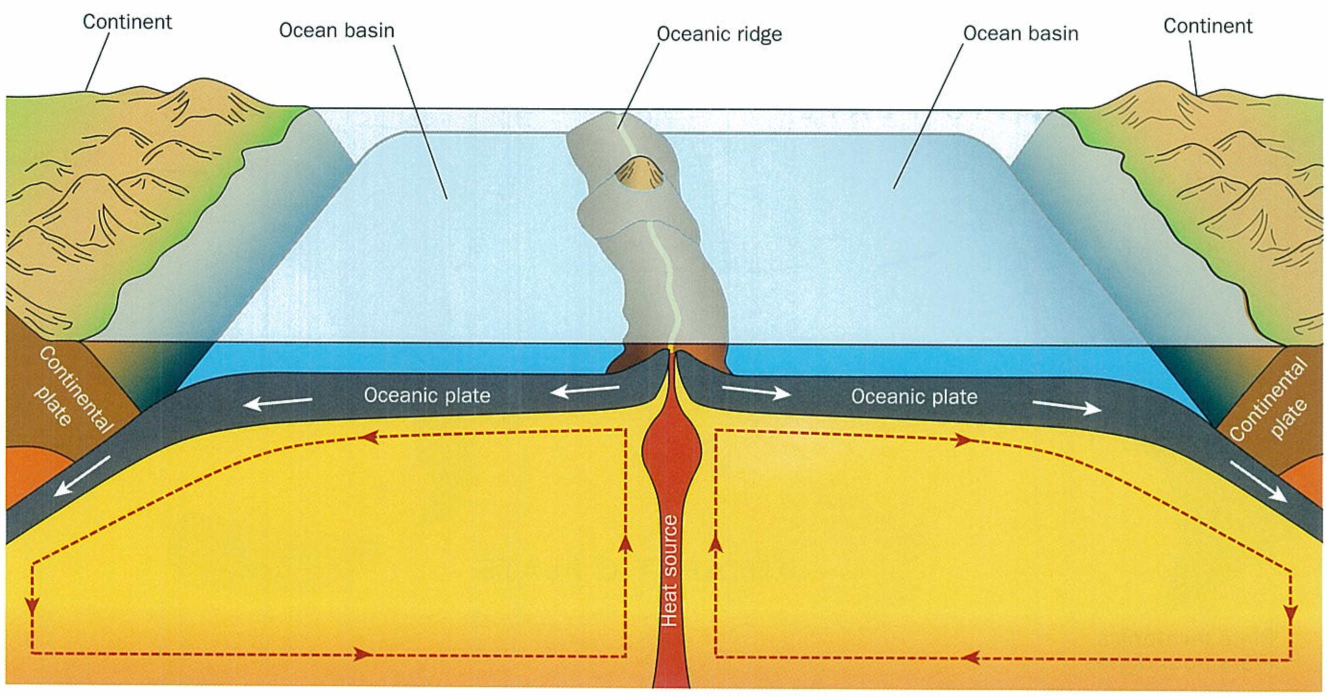


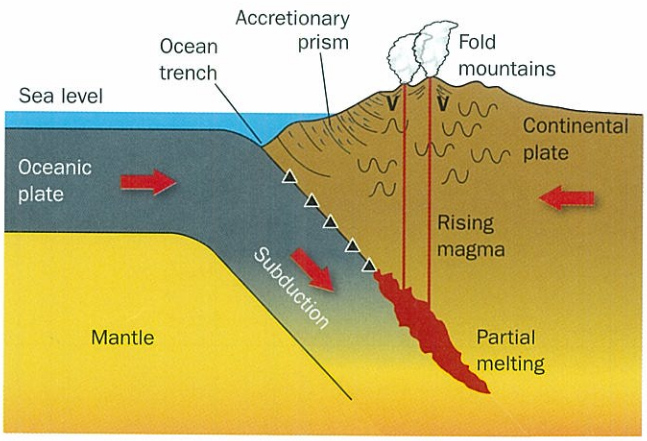
Fig. 3.2 Mechanisms of plate movement

> **2.** Using Fig. 3.1, and Table 3.2, name examples of each type of boundary.
>
> **3.** Using Fig. 3.1, explain why the Atlantic Ocean is growing by a few centimetres a year but the Pacific Ocean is shrinking.

Convergent plate boundaries

There are three different types of convergent plate margin, depending on the nature of the plates involved. The continental edge of a plate may meet the oceanic edge of a plate, the Andes being the classic example. However, two oceanic edges may meet, as in the Philippines, Japan or the Aleutian Islands, or two continental edges may meet, as in the Himalayas. In the first two of these, plate is destroyed and they are referred to as **destructive** plate boundaries.

Continental-oceanic convergent plate boundaries



V Volcano
▲ Earthquake focus (Benioff Zone)
Plate movement

Fig. 3.3 A cross-section through a continental-oceanic convergent plate boundary

The important surface features produced here are **fold mountains**, volcanic cones and **ocean trenches**.

Fold mountains form the highest of the world's mountain ranges. They are long, relatively narrow belts of mountains. They have parallel ridges and valleys and the main range is made up of a series of ranges. Flatter areas form plateaux in the mountains.

> **4.** Find a good atlas map of the physical geography of North America. The ranges of mountains in the west are collectively called the Western Cordillera (meaning western chains). List examples of the many sub-ranges, parallel valleys and inter-montane plateaux.

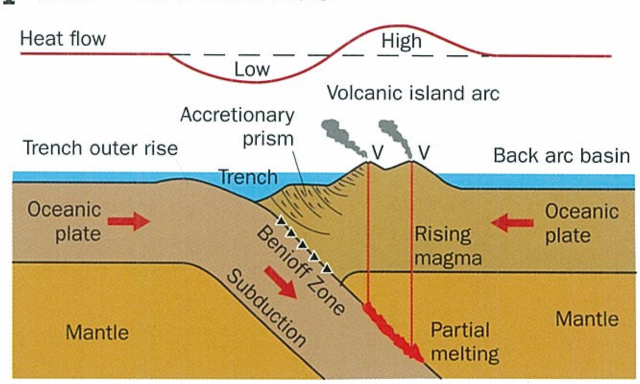
Fold mountains have been formed where compression caused by the plate collision has squeezed the layers of rock. When the upfolds or **anticlines** form the ridges and the downfolds or **synclines** form valleys this is referred to as **normal relief**. The folding takes place at great depths in the Earth, where the high temperatures and pressures make the rock behave as a plastic solid. As well as the mountains being uplifted, material at depth is forced downwards, leading to thickening of the Earth's crust in the mountain belt. Sediments deposited in the adjacent ocean and trench are scraped up against the leading edge of the continental plate and added to it. This is described as an **accretionary wedge** or **accretionary prism** (see Fig. 3.4).

Active volcanoes form high conical mountains in the ranges. These are usually strato-volcanoes (composite cones) made up of alternate layers of lava and ash and produced by explosive volcanic eruptions. The highest mountain in South America is Aconcagua, 6960 metres above sea level and an active strato-volcano. At these plate margins, the denser oceanic plate is forced beneath the less dense continental plate. This process is referred to as **subduction**. The oceanic plate is absorbed into the mantle and is destroyed. The subducted plate and the overlying mantle are partially melted (see Fig. 3.4.). The small pockets of magma gradually merge with each other and begin to rise to form volcanoes. Collectively, the mountain-building processes are referred to as **orogenesis**.

Offshore, there is no wide continental shelf and the ocean floor drops steeply into a long, narrow ocean trench which is parallel to the fold mountains. Here the water depth is about 10 kilometres, compared to a depth of 2–5 kilometres in the rest of the deep ocean floor. Trenches are a result of the surface being dragged down by subduction.

The sloping zone of earthquake foci shown in Fig. 3.4 is known as the **Benioff Zone**.

Oceanic-oceanic convergent plate boundaries



V Volcano
▲ Earthquake focus
Plate movement

Fig. 3.4 A cross-section through a oceanic-oceanic convergent plate boundary

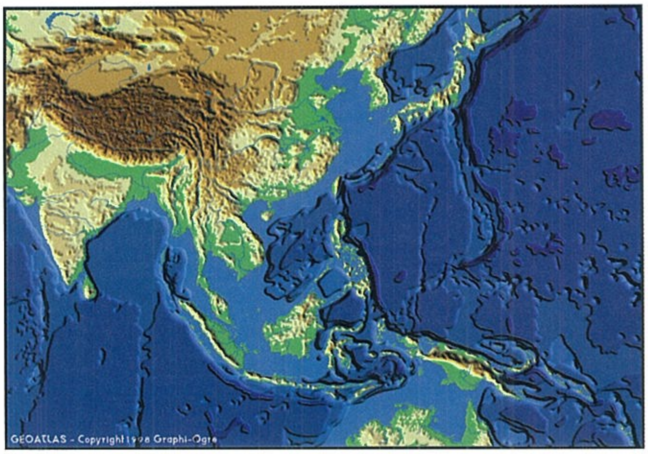


Fig. 3.5 The south-west Pacific Ocean showing island arcs and ocean trenches

The processes that occur at this type of margin are similar to those at the continental-oceanic convergent plate margins. Strato-volcanoes, ocean trenches, accretionary prisms and a Benioff Zone of earthquake foci all occur but there are no fold mountains like the Andes.

Instead the main features are **island arcs** and **ocean trenches**, best illustrated by the western part of the Pacific Ocean. An atlas map will show the Aleutian Islands and trench, the Kuril Islands and trench, Japan and the Japanese trench, the Philippines and the Philippine trench and the Mariana Islands and the Mariana trench. The latter includes the Challenger Deep, at 11 022 metres below sea level, the deepest point on the Earth's surface. The trenches are long, narrow crescents which present their convex sides to the Pacific Ocean and their concave sides towards the Asian continent. Fig. 3.5 shows these very well.

The island arcs are island chains with the same convexo-concave form. The island arcs are made principally of active strato-volcanoes but also by some sediments in an accretionary prism. The chemistry of the lavas is the same as those in the Andes and they form in the same way. As the two converging plates are both oceanic, the rocks at the edges of the plates have the same density. It is always the larger section of plate from the ocean side which is subducted, because of its greater mass. Heat flow (the heat flowing from depth to the Earth's surface) is less than normal over the trench with its cold descending slab, and higher than normal over the volcanic island arc.

Fig. 3.6 Mount Fujiama, Japan, a typical conical strato-volcano

Continental-continental collision boundaries

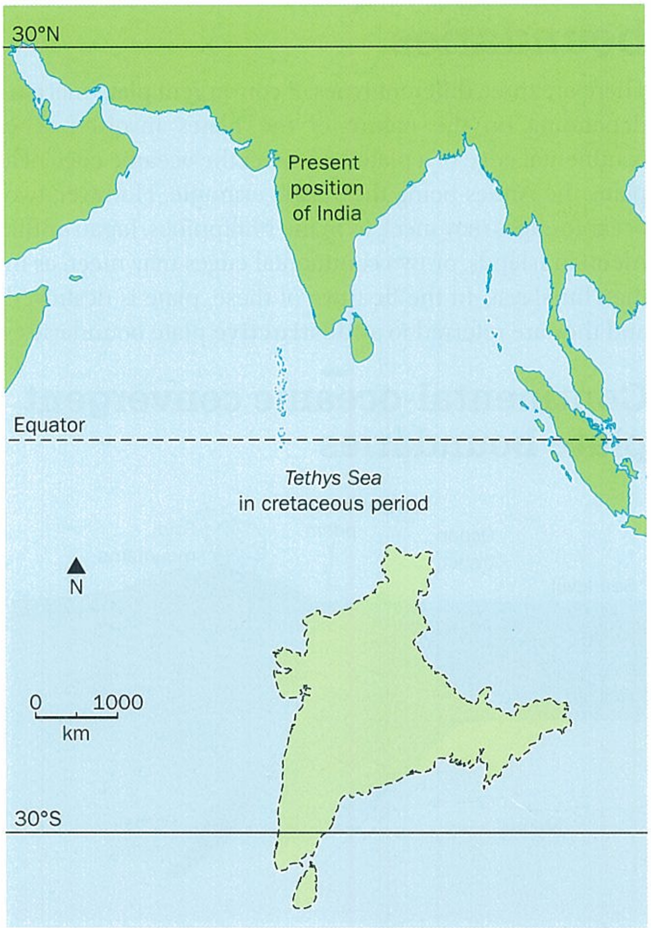


Fig. 3.7 The northward drift of India and the closure of the Tethys Sea

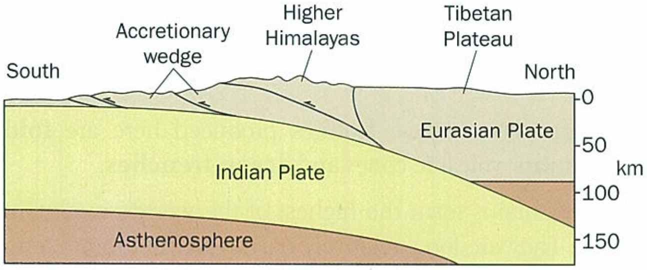


Fig. 3.8 Indian Plate is being forced beneath the Eurasian Plate. Sediments deposited in the Tethys Sea now form an accretionary wedge of folded sediments which is forced upwards to form the mountains.

Fold mountains are formed at these plate boundaries in the same way as at continental-oceanic convergent boundaries described above. Examples include the Himalayas, Tian Shan, Caucuses and Alps. As there is no subduction, there are no active volcanoes. The compressional stresses lead to the formation of earthquakes but these tend to have shallow and intermediate foci and not the deeper foci found in the Benioff Zones.

The fold mountains referred to so far are actively forming today at plate margins. However, there are examples of fold mountains that formed at ancient plate margins that are no longer active. These include the mountains of Scandinavia, Scotland and the Appalachians in North America. These areas do not have active volcanoes or major earthquakes.

Divergent plate boundaries

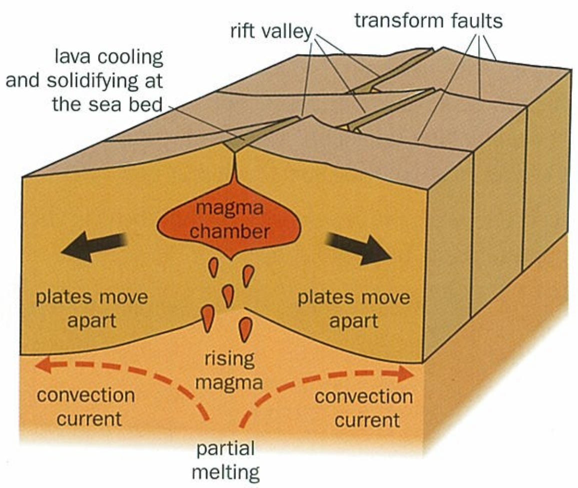


Fig. 3.9 A block diagram through a divergent plate boundary

Fig. 3.10 The deep ocean floor showing the form of ocean ridges

The divergent plate boundaries of the Earth are the sites of the great **oceanic ridges**. They are the most prominent topographic features on the surface of the planet and are well illustrated in Fig. 3.10. The ridges encircle the Earth; they are more than 50 000 kilometres long in places and more than 800 kilometres across. They rise an average of about 4500 metres above the sea floor. They are generally hidden beneath the ocean surface but exceptions are found, such as in Iceland. The Mid-Atlantic Ridge is one-third of the width of the ocean. Other examples include the East Pacific Rise and the Carlsberg Ridge in the Indian Ocean. The latter was named after the multinational brewing company which provided finance for research of the area.

The ridges' higher relief than the rest of the ocean floor is because the ridges consist of relatively hot, thermally expanded rock - an area of high heat flow. The ocean becomes deeper further away from the ridges; as the crustal material moves away from the ridge it cools, contracts and becomes lower. As Fig. 3.9 shows, the ridges are really a series of parallel ridges. There is a double central ridge separated by a **rift valley**. As a result of tension or stretching in the crust, a central block falls between parallel fault systems. The ridge is continuously offset by **transform faults**, sometimes referred to as **fracture zones** (see Fig. 3.9).

5. Explain the meaning of the terms 'lithosphere', 'asthenosphere', 'subduction', 'orogenesis' and 'island arc'.

Continental drift

The speculation that continents might have moved their positions was first put forward by Abraham Ortelius in 1596. The concept was developed by Alfred Wegener in 1912. The evidence was as follows:

Coastline fit

Wegener's theory was based in part on what appeared to him to be the remarkable fit of South America and Africa. The fit is best when the edges of continental slopes are used and features such as the Niger Delta are omitted.

Fig. 3.11 The fit of the Atlantic continents. The shaded areas show rocks more than 2000 million years old

Fossils, flora and fauna

There are similarities between plant and animal fossils found on the matching coastlines of South America and Africa. It would be physically impossible for most of these organisms to have swum or been transported across the vast oceans. One of these fossils is Mesosaurus, a crocodile-like reptile which lived in lakes and could not have crossed wide seas. This suggests the continents were joined 270 million years ago. It was also suggested that the flightless birds of the southern hemisphere (ostrich in Africa, emu in Australia, kiwi in New Zealand and rhea in South America) evolved separately from a common ancestor on the ancient super-continent of Gondwanaland. Then the super-continent split and the birds evolved separately and developed different features.

Fit of orogenic belts

When Atlantic coastlines are fitted together, orogenic belts (fold mountain belts) of the same age join up, e.g. the orogenic belts of North Appalachians, Newfoundland, northern Britain and Norway.

Fig. 3.12 The fit of orogenic belts across the North Atlantic

Fit of rock types

Precambrian rocks more than 2000 million years on either side of Atlantic join up when the Atlantic coastlines are fitted together (see Fig. 3.11). The same is true of sedimentary sequences 140–100 million years old on the Atlantic margins of both continents, indicating that the rocks were deposited in lakes and narrow seas between the continents.

Palaeoclimatic evidence

Fossils of tropical plants in Antarctica led to the conclusion that the continent must once have been situated closer to the Equator, in a more temperate climate where lush, swampy vegetation could grow. Permo-carboniferous glacial deposits in Africa, South America and India indicate a position over the South Pole at this time, showing that, when the glaciation took place, South America and Africa were probably joined.

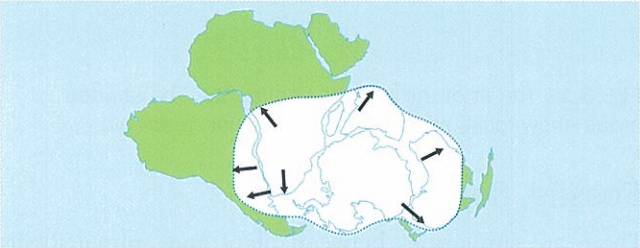


Fig. 3.13 The position of an ice sheet over the southern continents about 280 million years ago. The arrows show the ice movement directions indicated by features in the glacial deposits

6. Wegener noticed the remarkable fit of South America and Africa. The fit is best when the edges of continental slopes are used and features such as the Niger Delta are omitted. Why is this so?

Sea-floor spreading

Sea-floor spreading is the process of creation of new oceanic lithosphere at the ocean ridges and the divergence of the new lithosphere on either side of the ridge. The process begins with partial melting of rocks (a dark, dense rock called peridotite) in the upper mantle (the asthenosphere) beneath the ridge axis, in high temperature and low pressure conditions. The resulting magma forms pockets which collect together and rise to the surface. The magma is eventually extruded along the ridge as dark-coloured **basalt** lavas. The lava cools rapidly in contact with sea water and develops spherical structures known as pillows. Below this, some magma cools and solidifies below the surface to form the rock types dolerite and gabbro. The newly formed lithosphere cracks and diverges and the plates on either side of the ridge move slowly outwards from it, driven apart by mantle convection currents. Rates of divergence vary across the Earth but on either side of the Mid-Atlantic Ridge, Britain and North America are moving apart each year by 8 centimetres.

The crust beneath the oceans differs from the crust beneath the continents, as Table 3.3 shows.

	Oceanic crust	Continental crust
Thickness	Average 7 km (varies between 5 km and 10 km)	Average 35 km Maximum 90 km under mountain ranges such as the Himalayas
Structure	Layered structure: 1. Sediment 2. Basalt pillow lava 3. Dolerite 4. Gabbro	More complex structure: igneous, sedimentary and metamorphic rocks
Composition	Chemical composition of basalt	Overall chemical composition similar to granite
Chemistry	Rich in iron and magnesium	Rich in silicon and aluminium
Density	2.9 g.cm^{-3}	2.7 g.cm^{-3}
Age	Oldest rocks 200 million years	Oldest rocks 4000 million years
Physical state	Solid	Solid

Table 3.3 A comparison of the oceanic and continental crust

7. Study Table 3.3. Using information from Table 3.3 and what you have learned so far, explain the different ages of the oceanic and continental crusts.

Evidence for sea-floor spreading

The more recent evidence from ocean floor surveys confirmed that continental drift has occurred and led to the acceptance of plate tectonic theory:

- Age of the rocks of the ocean floor - this can be determined by be a technique called radiometric dating (e.g. the K-Ar method). At the crest of the ridge the basalts and the sediments which lie above them are very young, and they become progressively older away from the ridge crest.
- Thickness of sediment on the ocean floor - this increases with increasing distance away from the ridge - there has been more time for the sediment to accumulate. Older sediments are found on the sea bed at the margins of the oceans (see Fig. 3.14).

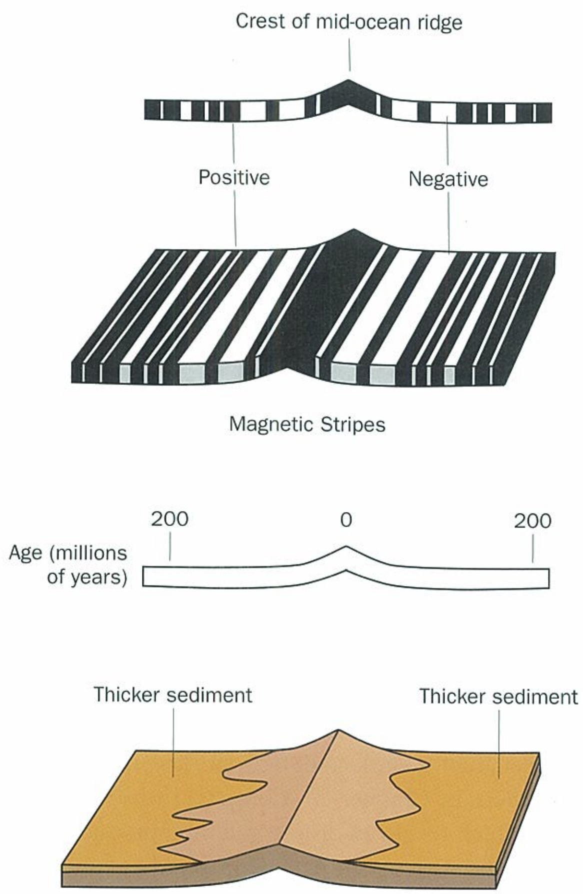


Fig. 3.14 Magnetic stripes, ocean floor sediments and the age of the ocean floor

- Direct satellite measurements of the width of the oceans - very precise measurements over time, of fixed points on the land masses, show the rate of ocean opening and closure.
- **Magnetic stripes** - iron minerals in the Earth's crust are magnetised by the Earth's magnetic field when the rock is forming, especially iron-rich basalt. These iron minerals tend to become aligned like tiny compass needles parallel to the magnetic field. The magnetism is weak but permanent, unless rocks are reheated. This is **palaeomagnetism** - fossil magnetism. It can be measured to give information about the Earth's magnetic field in the past.

The Earth acts as though it has a bar magnet through the centre. In the past there have been periodic geomagnetic reversals - reversals in the dipoles of the Earth's magnetic field - as though the bar magnet has 'flipped'. The youngest rocks at the ridge crest always have present-day (normal) polarity. Stripes of rock parallel to the ridge crest alternate in magnetic polarity (normal-reversed-normal, etc.), showing a symmetrical pattern on either side of the ridge. The stripes are of unequal width. This shows that the rate of spreading is the same on both sides of the ridge but that geomagnetic reversals do not take place at regular time intervals (see Fig. 3.14).

Hot spots

Although most volcanic activity takes place at plate margins, there are exceptions. A good example is Hawaii and the Emperor **seamounts** (a seamount is a submarine volcano). A hot spot is a volcano in a plate above a **mantle plume**. The plume is a stationary area of high heat flow in the mantle. It rises from great depths and generates magma. The age and distance apart of hot spot volcanoes are used to calculate the rate of sea-floor spreading. This is because the volcanoes form over the mantle plume then the plate movement carries them away.

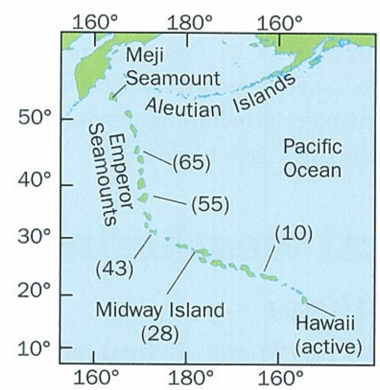


Fig. 3.15 The Hawaiian volcanic islands and the Emperor seamounts. The number in brackets is the age of the islands in millions of years

8. Using Fig. 3.15, describe the direction of plate movement
(a) between today and 43 million years ago
(b) between 43 and 65 million years ago.

9. The distance between Hawaii and Midway Island is about 320 kilometres. Calculate the rate of plate movement in centimetres per year during the movement of Midway Island.

10. How does it appear that the rate of plate movement has changed and what is the evidence?

Iceland is unusual because it is believed to be a hot spot on a plate boundary. One half of the island is on the North American Plate and the other half is part of the Eurasian Plate (see Fig. 3.16).

Fig. 3.16 The Mid-Atlantic Rift at Thingvellir, Iceland. The North American Plate is on one side of the rift and the Eurasian Plate is on the other

Weathering

Weathering is the decay and disintegration of rocks *in situ*, involving physical, chemical and biological processes. It excludes the erosional effects of running water, rivers, the sea, glaciers and the wind. The weathering processes do not transport the products away.

Rocks and minerals become adjusted to surface environments different from those in which they were formed. The products cover the Earth's surface as part of the **regolith** and go on to form new rocks. The regolith is the surface cover of loose, unconsolidated material including alluvium, glacial deposits, wind-blown sand, peat, scree and soil.

Physical weathering

Freeze–thaw

This process is also known as **frost shattering**. Water trickles into cracks such as joints during the day. At night this water freezes, expands by about 10 per cent and widens the crack. The stress produced by the expansion is greater than the resistance of the rock. Repeated freezing and thawing results in disintegration and the production of **scree** (**talus**) and **felsenmeer** (block fields). In temperate areas such as the highlands in the UK, these features are largely relics of the past periglacial climate rather than actively forming today. The critical feature for the process to be active is the number of freeze-thaw cycles rather than the intensity of the frost. This means that the processes is not active in winters in continental interiors where there is constant frost.

The shape and size of the particles produced by the process is controlled by the nature of the rock, especially lines of weakness such as joints, bedding planes and cleavage.

Scree is angular rock fragments. It falls from cliffs in areas of freeze-thaw action, falls down gulleys and is deposited as cone or fan shapes which may coalesce with one another. Such slopes are prominent features of many mountainous areas.

Fig. 3.17 Scree slopes in north-west Scotland

Heating and cooling (thermal fracture)

Large diurnal ranges of temperature in deserts cause rocks and minerals to expand during the day and contract during the night, resulting in disintegration.

Granular disintegration

This process is partly responsible for producing sand in deserts. Rates of expansion and contraction vary between:

→ different minerals

→ different axes of a crystal

→ crystals of different sizes.

Also, different coloured minerals absorb and emit heat at different rates. A pale-coloured rock like granite will reflect more heat than a dark-coloured one like basalt (see the albedo effect in Chapter 2). Complex stresses are set up in rocks which results in disintegration to produce mineral grains and the great sand seas or **ergs** found in some deserts.

Fig. 3.18 A sandy desert surface in Namibia

Block disintegration

This produces rock fragments not mineral grains and results in the features of the stony deserts known as **reg**. Scree slopes at the foot of cliffs and boulder fields are produced.

Fig. 3.19 A rocky desert surface in Namibia

Salt crystal growth

This process happens when salt solutions in the pores or joints of a rock crystallise. The crystals then expand and force the rock apart. The most effective salts are sodium sulfate, magnesium sulfate, sodium carbonate and calcium chloride. The process is particularly effective in temperatures of around 27 °C where temperature fluctuations produce expansion rates of up to 300 per cent.

Pressure release (dilatation)

This process, also known as **unloading**, affects areas where the ground surface is lowered by erosion. This removes weight from previously deeply buried rocks, e.g. a granite pluton which formed at immense pressure, several kilometres below the Earth's surface. This removal of weight leads to the expansion of the upper parts of the granite and allows cracks to occur parallel to the ground surface, sometimes known as **pseudo-bedding planes**. A similar process may occur where horizontal pressure is released by rock falls on a cliff face, allowing the growth of vertical cracks which, in turn, leads to further rock falls. This mechanism is significant after glaciation has occurred and can be caused by quarrying (see pages 87-90 on mass movement).

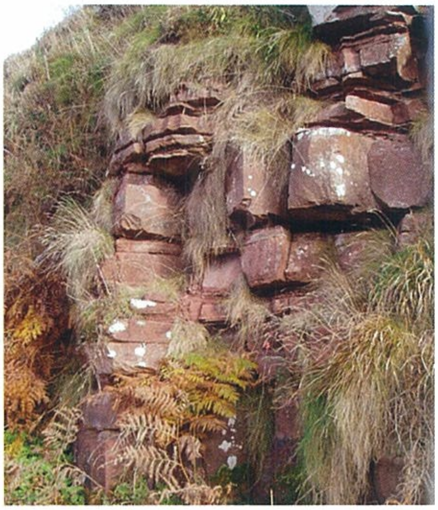


Fig. 3.20 In these alternating layers of sandstone and shales, the latter have been weathered more rapidly and have crumbled. The cliff surface is indented along the shale layers where vegetation is growing

Chemical weathering

Hydrolysis

This is when a mineral is broken down by a reaction with water. It is important in the silicate minerals that form most rocks, especially the mineral feldspar. The process usually occurs in acid conditions.

$$\underset{\text{feldspar}}{2KAlSi_3O_8} + 11H_2O + 2CO_2 \longrightarrow \underset{\text{kaolinite (clay)}}{Al_2Si_2O_5(OH)_4} + \underset{\text{silicic acid}}{4H_4SiO_4} + \underbrace{2K^+ + 2HCO_3^-}_{\text{ions in solution}}$$

The reaction shown above also includes some carbonation. The reaction produces a clay residue and various solutions which are removed in the groundwater and can be found in analysis of river water. You may see the variations in the formula written for hydrolysis.

Other clays are produced from other silicate minerals, e.g. montmorillonite.

Hydration and dehydration

Wetting and drying can cause the addition or removal of water from the molecules of some minerals, causing expansion or contraction which assist disintegration. The calcium sulfate minerals anhydrite and gypsum are affected.

$$\underset{\text{anhydrite}}{CaSO_4} + 2H_2O \longleftrightarrow \underset{\text{gypsum}}{CaSO_4.2H_2O}$$

Carbonation

This process affects the carbonate minerals that make up limestone, especially calcite, calcium carbonate. Rainwater contains the weak acid, carbonic acid, which forms as the rain absorbs atmospheric carbon dioxide. Carbonic acid then attacks the carbonate minerals.

$$\underset{\text{water}}{H_2O} + \underset{\text{carbon dioxide}}{CO_2} \rightarrow \underset{\text{carbonic acid}}{H_2CO_3}$$

$$\underset{\text{carbonic acid}}{H_2CO_3} + \underset{\text{calcite}}{CaCO_3} \rightarrow \underset{\text{calcium hydrogen carbonate}}{Ca(HCO_3)_2}$$

Calcium hydrogen carbonate is removed in solution (sometimes known as hard water) and is washed away down rivers. The muddy insoluble impurities in the limestone are left as a clay residue. The process is responsible for the characteristic limestone scenery known as karst. The chemical weathering of limestone is accelerated by pollutants such as sulfur dioxide and oxides of nitrogen.

Fig. 3.21 Spheroidal weathering of basalt. Water has penetrated the rectangular joints allowing chemical weathering to produce rounded blocks

11. Physical and chemical weathering are often considered separately; however, in nature the two are often linked. Explain how chemical processes can have a physical effect.

Organic action – vegetation roots

Biological weathering can have a physical effect on rocks as seen in the wedging effect of tree roots. Where the soil is shallow, the seeds and roots of trees find their way into natural cracks in the bedrock. As the seeds germinate and the roots get bigger, they make the cracks wider and deeper, eventually breaking up the bedrock. This effect can often be seen in road cuttings and quarries.

Other biological effects tend to assist chemical processes, for example as follows:

- The release of humic acids by decaying vegetation encourages hydrolysis.
- The release of carbon dioxide by plants encourages carbonation.
- A blanket of vegetation traps water and encourages a variety of chemical processes.

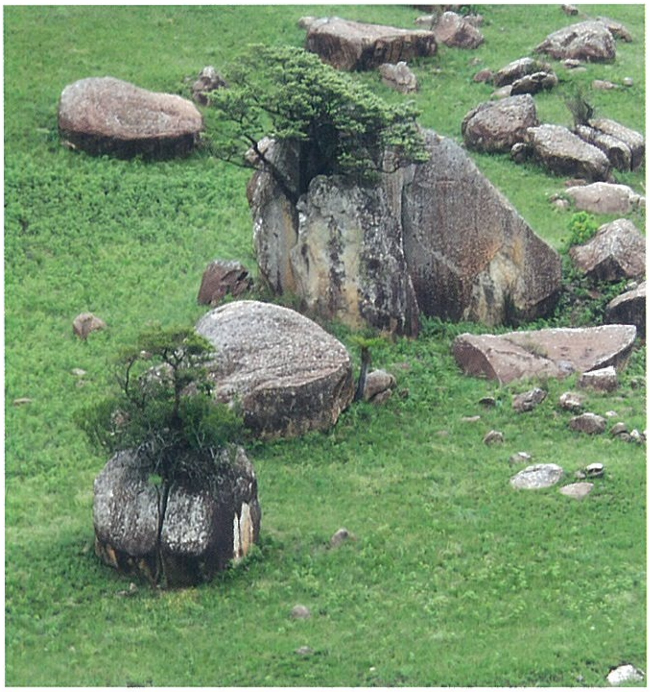


Fig. 3.22 The wedging effect of tree roots, Drakensberg Mountains, South Africa

Factors influencing weathering

Climate	Climate determines which weathering processes will occur and the rate at which they occur. This is considered in more detail below.
Rock structure	Weaknesses such as joints, bedding planes and cleavage allow water penetration and increase both physical and chemical effects (see Fig. 3.20). These weaknesses also control the size and shape of the weathered fragments. Good examples are the spheroidal weathering of dolerite, the formation of tors in granite and the formation of scree slopes.
Rock texture	In general, coarse-grained rocks weather faster than their fine-grained equivalents because the weathering of one mineral in the rock tends to weaken the fabric of the rock to a greater degree. Igneous rocks have a greater resistance to physical disintegration than sedimentary rocks because of the greater strength of interlocking crystalline textures in comparison with granular ones.
Rock composition	The minerals which form at the highest temperatures are the least stable at surface temperatures. This means that minerals in the dark-coloured rocks such as basalt weather faster than those in pale-coloured rocks such as granite.

	Minerals in basalt	**Minerals in granite**
Most susceptible	olivine plagioclase feldspar pyroxene	biotite
Least susceptible		orthoclase feldspar muscovite quartz

Slope processes

Mass movement

Mass movement (also known as mass wasting) is the term for the downslope movement of rock and weathered debris by gravity alone. It does not include the work of erosive agents such as running water or glaciers. Care is needed when reading accounts of mass movements because phrases such as 'landslide' may not be used in a technically correct way.

Mass movement	Creep and solifluction	
	Debris flows and lahars	
	Slope failures	Slides
		Falls

Table 3.5 Types of mass movement

Fig. 3.25 Terracettes caused by soil creep

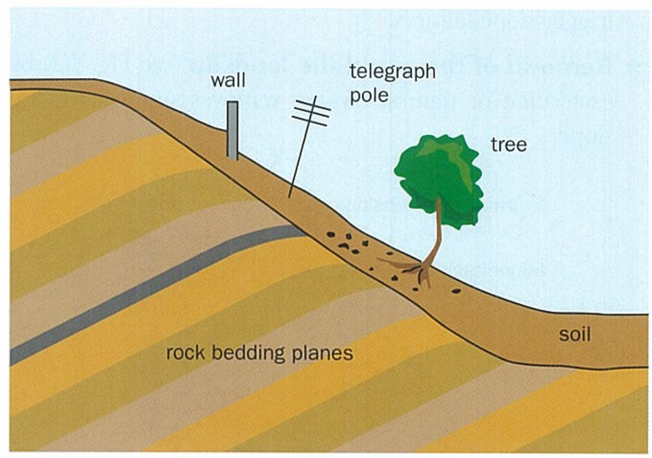


Fig. 3.26 Evidence for soil creep

Creep

This is the slow, downslope movement of unconsolidated material and soft rocks. This movement is rarely more than 1–2 centimetres a year. It is the result of several different processes:

→ Clay-rich material is liable to **plastic flow**. This is more likely to happen on saturated, thick, surface deposits on steeper slopes. It can also be affected by pressure from overlying cap rocks or human constructions.

→ Freezing and thawing of water in the surface layers of the clay or soil can produce **heave**. The expansion of water on freezing causes bulging of the surface parallel to the slope. On thawing, the material drops back vertically leading to a net downslope movement of the particles.

→ Wetting and drying causes clays to expand and contract, causing heave to occur in the same way as freezing and thawing.

In areas of permafrost, the waterlogged summer conditions lead to accelerated creep known as **solifluction**, although this may involve some viscous flow.

Creep may be responsible for the convexo-concave rolling landscapes found in temperate areas such as western Europe. The process is also thought to be responsible for the small ridges across hillsides known as **terracettes**.

13. Study Fig. 3.26. Describe the evidence for soil creep shown in the diagram.

Flows

Often referred to as mudflows (see Fig. 3.45), these involve the rapid movement of rock and weathered debris mixed with water down valleys. They do not involve shearing and are a turbulent, structureless mixture of sediment and water. Flows are linked to the following factors:

→ steep slopes

→ narrow valleys

→ removal of vegetation and construction projects

→ a thick regolith, therefore they are common in the tropics where deep chemical weathering occurs

→ heavy rainfall to saturate the ground

→ a slope failure or slide (see below) which may trigger the flow

→ earthquakes or traffic vibration; earthquakes can also cause liquefaction of saturated material.

These conditions may be found on the slopes of active volcanoes where the mudflows are termed **lahars**. In this case loose, volcanic ash combines with run-off from convectional rainstorms produced by eruptions.

Mudflows have devastating effects in less-economically developed countries, especially when the narrow valleys are densely populated. However, they affect affluent areas too.

Slides

Landslides are single dramatic events when a section of a hillside becomes unstable, shears away and moves downhill. The shear stresses in the slope exceed the shear strength of the soil or rock. The slopes in question could be natural or the result of human activity such as road cuttings, embankments and spoil heaps.

Factors leading to slope failure include the following:

→ **Slope angle** – the steeper the slope the greater the potential for instability.

→ **Geological structure** – fractures such as bedding planes dipping out of the slope increase the possibility of slippage.

→ **Rock type** – vertical cliffs may be quite stable in some rocks whereas some clay slopes are unstable on slope angles of less than 10 degrees. Layers of impermeable rock trap water above them, leading to highly lubricated layers.

→ **Amount of water present** – water increases the weight of soil or rock. Pore water pressure decreases the shear strength of the material, with saturated clays being particularly unstable. Heavy rain or snow melt can trigger slope failures.

→ **Removal of the toe of the landslip** (see Fig. 3.2) by excavation or natural erosion removes support for the slope.

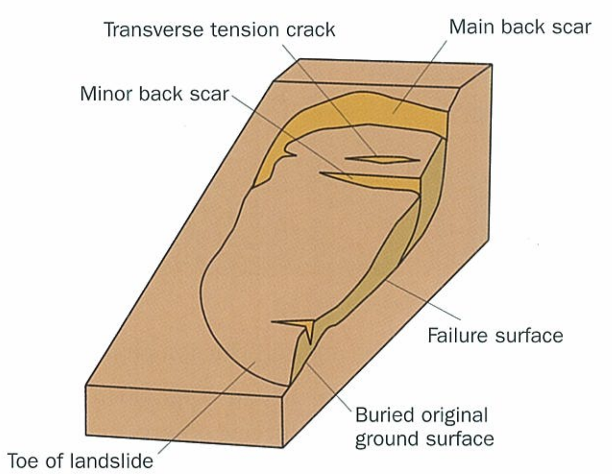


Fig. 3.27 The effect of a landslide on the surface. The failure surfaces can be planar as well as curvilinear. Notice the curved slip faces and the rotational movement which tilts the slope backwards. The toe of the slip is often an area of uneven, deformed ground

Fig. 3.28 An old landslide at Black Combe, Cumbria, UK. Notice the main back scar

→ **Loading of the head of the slope** by construction projects can cause the slope to fail.

→ **Vibrations** from explosions, earthquakes or heavy traffic temporarily increase stress.

These factors work by either increasing the shear stresses in the slope or reducing the shear strength of the soil or rock.

Case study: The Vaiont dam disaster, Italy, 1963

This landslide resulted in the loss of 2600 lives. A dam 266 metres high was constructed across the Vaiont River to produce hydro-electricity. The site was a deep, narrow valley chosen to store large volumes of water. Slippage started when the reservoir started to be filled, so the slope was reinforced. When the reservoir was filled completely, water seeped into the rock layer, increasing pore water pressure and reducing cohesion. On 9 October 1963 heavy rainfall resulted in 270 million cubic metres of rock sliding into the reservoir at a speed of 25 metres per second. This created a wave 100 metres high which flowed over the dam and into the valley below.

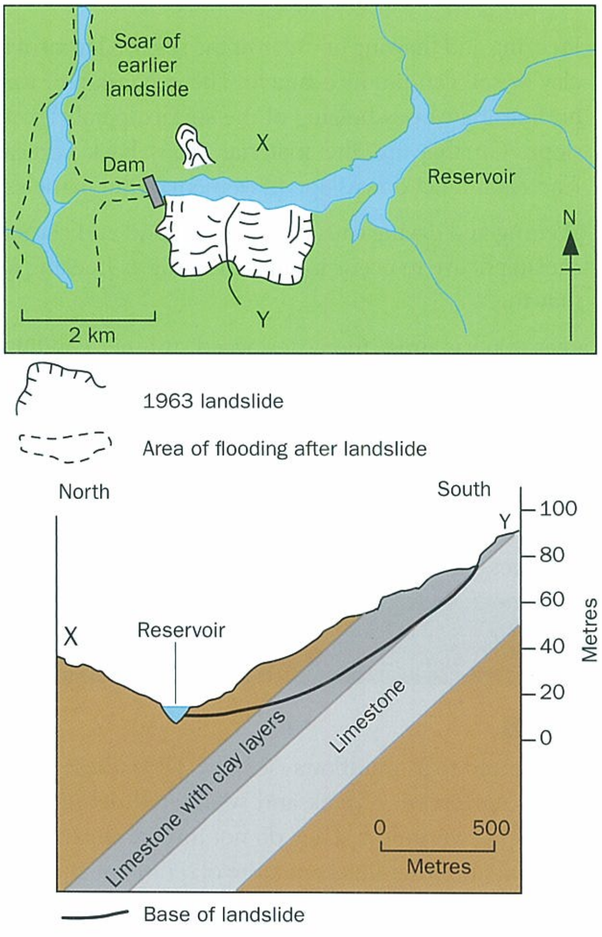


Fig. 3.29 The Vaiont dam landslide

Rock type	**Sandstone** The cement is generally attacked to produce granular disintegration. Resistance depends on the nature of the cement. For example, quartz cement is most resistant, while $CaCO_3$ cement is prone to carbonation. Joints and bedding planes may provide lines of weakness for physical or chemical attack. **Shale** The clay minerals in shale are weathered products of other rocks, therefore tend to be resistant to chemical weathering. Iron oxides and sulfides are commonly present and these tend to oxidise and hydrate, resulting in changes in volume and disintegration. Laminations (and porosity in clays) allow water penetration, increasing both physical and chemical attack. The softness of the rock also increases susceptibility to physical weathering. Shales and clays usually form lowlands as they are easily weathered (and eroded). **Slate** Chemical reactions occur similar to those in shale. Slate is chemically resistant to many reactions, but iron compounds, e.g. pyrite, are prone to oxidation, leaving brown stains; weathered cubes of pyrite often leave holes in slate. Cleavage may allow water penetration and allow freeze–thaw action to produce 'flat' scree fragments. **Basalt** Basalt is rich in minerals which are less resistant to decay by hydrolysis (see the list above). Basalt is often highly weathered, as seen in the rusty residues of iron oxides. The resulting soils are dark coloured and highly fertile due to the presence of a wide range of elements held in montmorillonite clay. Joints allow water penetration which encourages chemical decay and physical processes leading to block disintegration. **Dolerite** Chemical decay occurs in the same way as described for basalt. **Spheroidal weathering** (see Fig. 3.21) is controlled by the joint pattern and is often a sub-surface process. **Limestone** The carbonate minerals are weathered by carbonation and removed in solution. Insoluble clay minerals are left as a residue. Joints allow water penetration and deeper weathering. **Granite** The quartz and muscovite in granite resist chemical decay and are left as a residue of sand grains and mica flakes. Feldspar and other minerals break down by hydrolysis to produce clay minerals. Joints allow water penetration and deeper weathering.
Vegetation	In general, increased amounts of vegetation increase the rate of chemical action through the release of organic acids, important in processes such as chelation. The increased level of carbon dioxide from plant respiration forms carbonic acid when dissolved in water and increases rates of carbonation. Rates of physical weathering will decrease due to the thermal insulation of the vegetation which decreases frost action and thermal effects. Direct biological weathering, through the growth of plant roots into joints and along bedding planes and wedging rock apart, will increase.
Relief	The effect of relief is largely because of its indirect effect on climate. For example, in temperate areas where chemical weathering is usually dominant, freeze–thaw action may be important in mountainous areas. Rainfall totals tend to be higher in upland areas and temperatures colder, again increasing rates of physical weathering such as freeze–thaw action. Slope processes, such as landslides, can result in the exposure of previously unexposed, bare rock which then becomes susceptible to weathering. In lowland areas, unweathered rock may be protected by thick layers of soil and weathered material. The accumulation of water at the base of slopes may also provide more water for chemical processes to take place. Aspect of different slope faces may also affect rates of weathering. In the northern hemisphere, rates of physical weathering are greater on north-facing slopes, which experience more freeze–thaw cycles due to the lack of direct sunlight. The opposite is the case in the southern hemisphere.
Human activity	Humans have increased rates of weathering by increasing the concentrations of chemical pollutants in the atmosphere by industry, power stations and vehicle emissions. The increase in gases such as carbon dioxide, sulfur dioxide and nitrogen oxides has lead to increased acidity of rainfall. This acid rain increases rates of carbonation and hydrolysis. Removal of vegetation can result in a decrease in chemical and biological weathering, e.g. through a reduction in organic acids.

Table 3.4 Factors influencing weathering

Climate

Polar and sub-polar areas

These high latitude areas are affected mainly by freeze-thaw action. These conditions may also occur on mountains in temperate areas. The degree of activity depends on the number of freeze-thaw cycles rather than the degree of frost, therefore the rate of weathering in very cold areas is restricted.

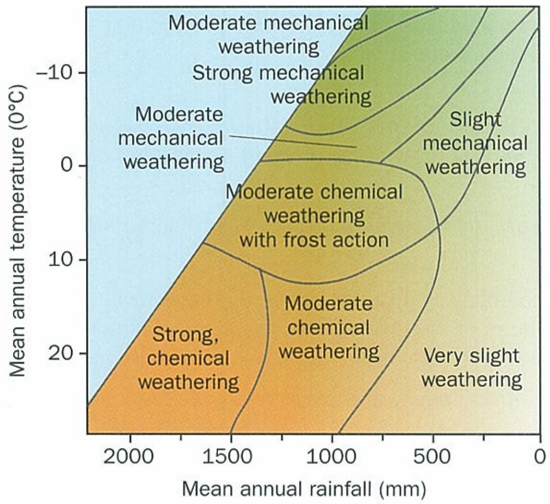


Fig. 3.23 The effect of climate on weathering, as described by Peltier in 1950

Chemical action is restricted by the cold temperatures which slow rates of chemical reactions. However, carbon dioxide is more soluble at low temperatures so carbonation can occur. Hydration may occur in waterlogged areas in summer.

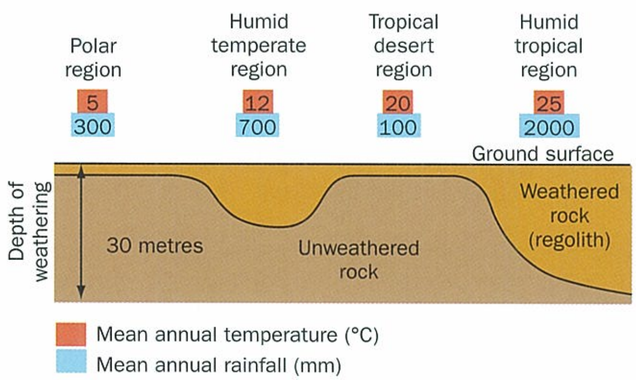


Fig. 3.24 Rates of weathering in different climates

Humid temperate areas

Physical weathering is minimal; the screes of upland areas may be relict features of periglacial conditions in the Quaternary period (the last 2 million years). Similarly, the tors of areas such as Dartmoor in south-west England may also have formed in past climates, although in this case possibly in warm conditions in the Tertiary period when rates of chemical weathering were greater.

All the chemical and biological weathering processes are significant due to the wet climate and the blanket of vegetation which causes the biological effects. Pollution effects are important, especially in urban areas.

Arid and semi-arid areas

Rates of weathering are the slowest on Earth in these areas. This is illustrated by well-preserved archaeological remains, e.g. Cleopatra's Needle weathered more in 10 years in the wet, polluted atmosphere of London than in 3500 years in the Egyptian desert.

Chemical action is probably very slow due to the lack of moisture. Salt crystal growth, and physical expansion and contraction, due to the large diurnal ranges of temperature, may lead to granular disintegration, block disintegration and exfoliation (see Chapter 10).

Humid tropical areas

These areas have the most rapid rates of weathering on Earth. The regolith is often up to 40 metres deep and rocks are observed to weather significantly in decades. Rates of chemical reaction are accelerated by the hot, wet conditions; in particular, the increased ionisation of water increases the rate of hydrolysis of silicates. The increase rate of weathering at higher temperatures is known as Van't Hoff's Law.

12. Study Fig. 3.23 and the information on weathering processes. Describe the rates of weathering and weathering processes that are likely to occur in each of the following conditions:

(a) mean annual temperature 25°C and mean annual precipitation 2000 millimetres

(b) mean annual temperature 15°C and mean annual precipitation 1000 millimetres

(c) mean annual temperature 20°C and mean annual precipitation 250 millimetres

(d) mean annual temperature 5°C and mean annual precipitation 1000 millimetres.

14. Study Fig. 3.29. Explain how the geology of the area led to the landslide.

Falls

Rock falls from vertical faces share many of the features of landslides and are caused by similar factors. In addition, undercutting of the base of the cliff by a river or the sea are common factors.

Rock falls reduce horizontal pressure on a cliff face, allowing the growth of vertical cracks which, in turn, lead to further rock falls. This mechanism is significant after glaciation has occurred. Glaciers excavate deep valleys and support steep valley sides. After the ice has melted the sides are less supported and liable to rock falls.

Rock falls produce scree (talus) which accumulates as cones or fans at the base. These may eventually join together to produce a continuous slope like those in Fig. 3.30 or huge boulders like those shown in Fig. 3.31. Some fragments may bounce significant distances. Scree slope angles rarely exceed 40°, despite their appearance.

The angle of the scree slope depends on:

- the size of the rock fragments
- the shape of the rock fragments
- the height of the cliff (or 'free face') through which the fragments have fallen.

15. Suggest the effect that each of the factors listed above is likely to have on the angle of a scree slope. Illustrate your answer with diagrams.

Fig. 3.30 Scree slopes on Arkle, a mountain in north-west Scotland

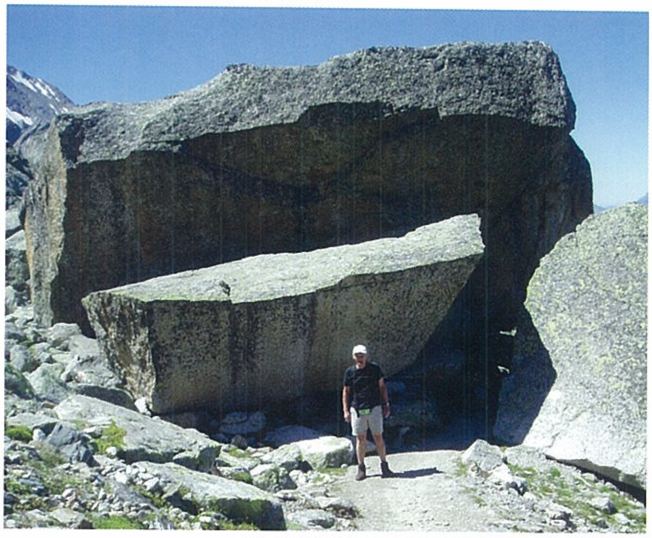


Fig. 3.31 Boulders produced by rock falls in the French Alps

Erosion processes on slopes

The slope processes described above are all types of mass movement in that they are all independent of running water. However, running water does play a part, particularly where **rainfall intensity** exceeds the **infiltration rate** and **overland flow** occurs. The effects are often increased by human activity such as deforestation, over-grazing, burning or cultivation which leaves the soil bare. On gentle slopes, water may run off the surface as a uniform sheet, causing **sheet erosion**. On steeper slopes the water becomes concentrated in channels leading to **gully erosion**. Ploughing down the slope rather than across it is also a factor. The intermediate stage between the two produces fine channel networks known as **rills**.

Fig. 3.32 Gullies on farmland in Kwazulu Natal, South Africa

Intense rainfall with large droplets can have a direct erosive effect on bare soil known as rainsplash erosion. The effect is greatest on steeper slopes because more of the energy of the impact is used in pushing soil down the slope.

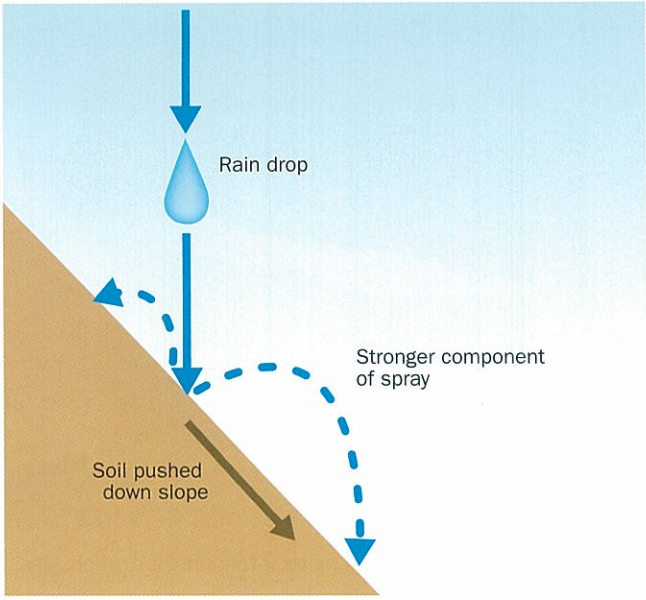


Fig. 3.33 Rainsplash erosion

The human impact

How human activity can result in mass movement on slopes

Excavations

Perhaps the most common way that human activity can result in mass movement is where the ground is removed, e.g. in road and railway cuttings, to make level ground for a building, or in quarries. In areas prone to mass movements (e.g. where there are soft or unconsolidated rocks, where the rock strata dip down the slope, or where there are alternating permeable and impermeable layers) this can create a slope which is too steep to be stable and therefore liable to failure.

Where an excavation removes the toe of an old landslip (see Fig. 3.27) this can re-activate the feature and lead to further movement. Other, smaller excavations are those for road and railway cuttings, and for the foundations of buildings. New slopes are being created and this must be done in a way that ensures that the new slopes are stable and not liable to catastrophic mass movements.

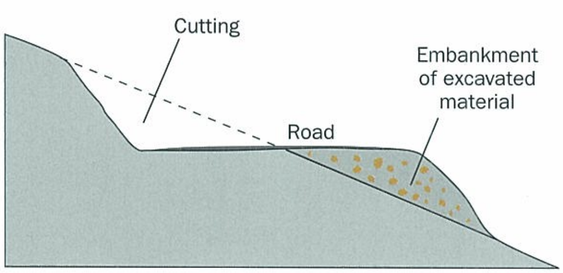


Fig. 3.34 A cross-section through a road constructed across a slope. This method raises various questions. Is the cutting sufficiently gentle to ensure that mass movement will not occur? If not the measures described in Fig. 3.37 should be employed. Is the embankment of excavated material stable? Is water drainage from the road adequate and will it cause mass movement or erosion? Will the material in the embankment settle over time and cause the road surface to be uneven?

Waste heaps

Often waste heaps from quarrying and mining have steep slopes and are made of material which is unconsolidated or highly porous.

Fig. 3.35 The spoil heaps of the quarry

The newly created steep slopes may be unstable and liable to slope failures. One example of this was the catastrophic slope failure of a coal mine spoil tip in the village of Aberfan, near Merthyr Tydfil, Wales, on 21 October 1966, which killed 116 children and 28 adults. It was caused by a build-up of water in the accumulated rock waste, which started to move downhill as a mudflow.

Loading by building

Building on the top of a slope liable to landslip can add sufficient mass to the ground that it will trigger the process described in Fig. 3.27.

Loading by water

When rock cuttings or building projects are carried out, drainage may be disturbed, diverting water into these areas. Water has a lubricating effect on unconsolidated material and saturated clays are unstable, all of which can lead to landslips. However the extra weight of water in the rock is also a factor. If the saturated sands or clays are shaken by an earthquake then liquefaction may occur. Before the earthquake, the water pressure in the sand is relatively low, but shaking causes the water pressure to increase, allowing the sand particles to move relative to each other, acting like a liquid.

Removal of vegetation

Deforestation, construction projects or even leaving land bare after cultivation can increase surface runoff leading to mudflows in susceptible areas.

Case study: The Merriespruit tailings dam disaster, Virginia, Free State, South Africa

Gold is extracted from the ground at very low purities and the processing produces large quantities of fine-grained waste mixed with water known as tailings or locally as 'slime'. This waste is deposited in 'slime dams' which are prominent features of the landscape, appearing as rectangular, steep-sided, flat-topped hills.

Fig. 3.36 Tailings from gold mining, Johannesburg, South Africa. The Central Business District (CBD) can be seen in the background

Like many others in South Africa, the Merriespruit tailings dam was made by constructing a 'daywall' perimeter which was allowed to settle and dry out. This activity was often done during the day under supervision. After this and often at night, the slurry was pumped into the 'nightpan' between the perimeter walls. A drainage system was installed in the dam to drain away the water plus any rain water.

There were 250 houses in Merriespruit, a suburb of the goldfields town of Virginia, when the dam was constructed in 1978.

Late in the afternoon on 22 February 1994 there was a thunderstorm and about 50 millimetres of rain fell in 30 minutes. That night the tailings dam failed and flooded Merriespruit when 600 000 m^3 of liquid slurry flowed 4 kilometres away from the dam. The nearest houses were located 300 metres downslope of the dam and when the wave of water and slime reached them it was 2.5 metres high. There was widespread devastation and environmental damage, 17 people were killed and 80 houses were destroyed. Inadequate systems for draining water from the dam were blamed for the disaster.

Traffic vibrations

Movement of heavy vehicles is not a sole cause of mass movement but it can be a trigger for movements.

How human activity can result in erosion on slopes

Removal of vegetation

This could be through:

- overgrazing,
- soil exposure during cultivation
- cultivating in areas of low rainfall
- construction projects.

All these activities can lead to bare surfaces liable to rainsplash erosion, sheet erosion, rill erosion and gullying. In extreme cases, after heavy rainfall, it may also lead to mudflows.

Ploughing up and down slopes

Ploughing up and down steep slopes creates pathways for surface runoff which can lead to the development of rills.

Destroying soil structure

Poor agricultural practices such as growing too many crops in an area (overcropping) or allowing the organic content of the soil to deteriorate can lead to the destruction of the crumb structure which helps to bind the soil together. This leaves the soil loose and prone to erosion both by wind and running water.

Case study: Railway landslide in Cumbria, UK, 1995

Landslides are surprisingly common on railway cuttings. The line from Settle to Carlisle, UK, runs through an area of Carboniferous shales and sandstones and the alternating impermeable and permeable rocks are prone to slippage. At 18:55 on 31 January 1995, a train was derailed by a landslide on this line at Aisgill. It was dark and raining heavily. The train was hit by a train travelling in the opposite direction. The conductor of the first train was fatally injured in the collision.

Strategies to reduce mass movement and its impact on slopes

The methods described below are generally used to prevent slides and falls, often on artificially-created slopes.

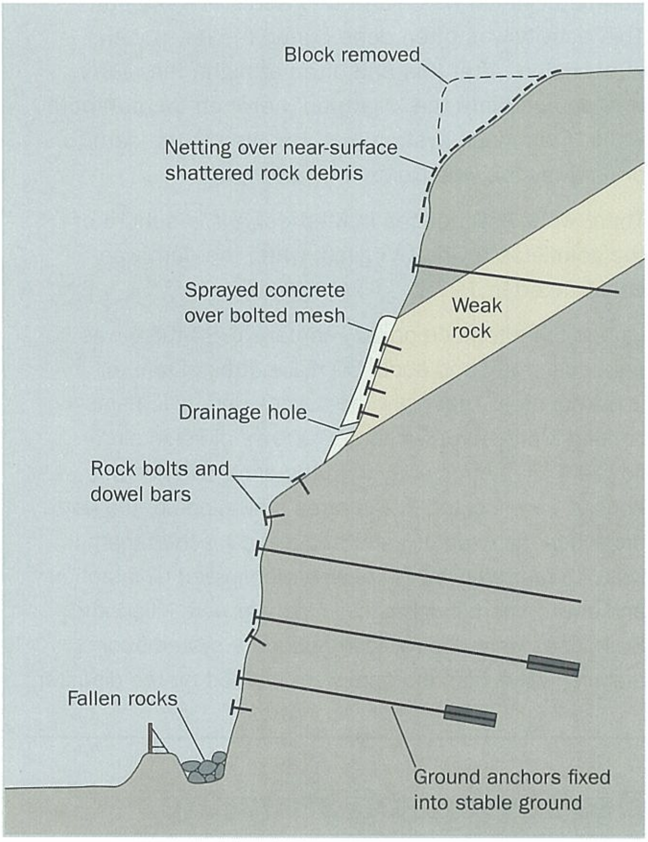


Fig. 3.37 Rock slope stabilisation

Pinning (including rock bolts, dowel bars and ground anchors)

Fig. 3.38 Rock bolts

These methods involve drilling a long hole through loose blocks into the stable rock beyond. A metal rod is inserted and fixed in place with a resin or an expansion bolt. A metal plate is then bolted onto the outside of the rod. Rock bolts and dowel bars are relatively short but ground anchors may be long cables used to stabilise whole landslide areas.

Netting

Fig. 3.39 Netting

Metal netting is fastened to road cuttings to prevent loose blocks falling on the road below.

Gabions

Fig. 3.40 Gabions

Gabions are boxes made of metal mesh. They fold flat for transport and are assembled on-site and filled with rocks. They do have other purposes but they may be used to stabilise the toe of a landslip.

Drainage

Fig. 3.41 Beneath the crash barrier on this road, a gravel-filled trench provides drainage

Excess water on slopes adds mass, provides lubrication and is often a key factor in the formation of flows and slides. Moving water away from vulnerable slopes is one of the most important ways of preventing these mass movements. The simplest and cheapest way of doing this is often to dig a trench, as shown in Fig. 3.41, and fill it with a highly permeable aggregate (gravel).

Grading

Fig. 3.42 A gently graded cutting. The slope here consists of strata dipping towards the road. Alternating layers of permeable limestone and impermeable shale make it unstable after heavy rain and liable to slip along the bedding planes. For this reason the cutting has been made with a gentle slope

Slope angle is a key feature in mass movements. The steeper the slope, the more potentially unstable it is. Where slopes are artificially created, they need to be made more gentle if there is a risk of movement. However, this requires more excavation and produces more waste rock to be transported away and disposed of, increasing costs. Similarly, the slope angle of natural slopes can be decreased to reduce risk. The process of making slopes more gentle is referred to as grading.

Fig. 3.43 The rocks in this cutting are stable as they dip at right angles to the slope (the same would be true if the rocks dipped away from the road and into the slope). It has been possible to make a steep cutting and save costs

Afforestation

Planting trees and other vegetation is often used to reduce soil erosion but it can also reduce the risk of mass movements. The trees have various effects. Trees increase interception and therefore evaporation losses are greater. Roots absorb water and therefore increase transpiration losses. This means that there is less surface runoff (which might otherwise result in mudflows) and less infiltration to add mass to the rocks. The roots themselves may have the effect of binding soil and loose rock.

Grouting

This involves injecting permeable rocks with cement to reduce pore water and increase strength.

Shotcrete

Loose rock surfaces can be sprayed with concrete which can help to prevent loose blocks falling from the slope.

Mapping hazards

Many landslides occur when old landslides, which have moved many times in the past, are re-activated as a result of heavy rainfall, excavations or earthquakes. The case study of California in this chapter illustrates this (see page 92). Detailed mapping of these features can help planners to decide which areas should be avoided by future house or road building or to decide what precautionary measures need to be taken. This mapping can make use of historical accounts but often looks for topographic features like those described in Fig. 3.27.

Strategies to reduce erosion on slopes

Method	Erosion prevented	
	Wind	Water
Terracing		✓
Contour ploughing		✓
Crop rotation	✓	✓
Fallow periods	✓	✓
Strip cultivation and inter-cropping	✓	✓
Cover cropping	✓	✓
Reducing stock density	✓	✓
Check dams		✓
Filling gullies		✓
Afforestation	✓	✓
Shelter belts (wind breaks)	✓	
Dry farming	✓	
Irrigation	✓	✓

Table 3.6 Strategies for reducing erosion on slopes

16. Explain how each of the strategies in Table 3.6 can reduce erosion on slopes.

Case Study: California and Los Angeles

Slides and flows are common in California, damaging roads, railways, pipelines, electricity cables, and other infrastructure. The suburbs of Los Angeles are particularly affected.

The causes are as follows.

Intense rainfall

Downtown Los Angeles has an annual precipitation of only 385 mm, which mainly occurs during the winter and spring, with heavy rainfall during winter storms. The coast gets slightly less but the hilly suburbs get slightly more. However, there is great variation from year to year. Heavy rainfall on dry ground can lead to mudflows and loading of the ground resulting in landslides.

Soft, poorly-consolidated rocks

The geology of the area consists of relatively young Neogene and Pleistocene marine sediments deposited between 15 million and 1 million years ago.

Steep relief

Los Angeles rises from sea level to 1547 m (Mount Lukens) in the form of a basin. The central parts of the city are flat but the outer suburbs are hilly, for example areas such as the San Fernando Valley, the Santa Monica Mountains, Mount Washington, Boyle Heights and San Pedro.

Road and housing construction

Los Angeles (population 3.88 million in 2013) has grown rapidly outwards into hilly districts prone to mass movements. Construction in these hilly districts can add load to unstable slopes and road cuttings in these areas may also be unstable.

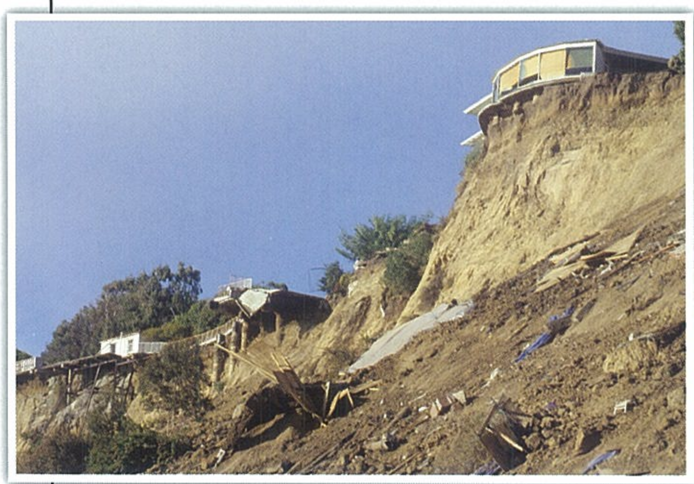


Fig. 3.44 Landslide damage in the Pacific Palisades area of Los Angeles

Oil and water extraction

Groundwater extraction for water supply and petroleum extraction have both caused ground subsidence. In 1963 in the Baldwin Hills a dam collapsed as a result of this.

Earthquakes

The San Andreas fault system and other active faults in the area can trigger landslides on slopes affected by the factors listed above. As mentioned earlier in the chapter (pages 85–86), earthquakes can also cause liquefaction of the ground.

Examples

Although slope failures are common in California, some of the most significant include:

- April 18, 1906. A major earthquake in San Francisco triggered numerous landslides, including the Devil's Slide in San Mateo County. The latter is still active today.
- January 3–5, 1982. Landslides in the San Francisco Bay area killed 25 people and caused at least 66 million USD in damage.
- January 10, 2005. A mudslide in La Conchita killed 10 people and destroyed 18 homes.

Mudflows in southern California, December 2010

In one week in December 2010 the area received half of its annual average rainfall and some streets flooded. California Governor, Arnold Schwarzenegger, declared a state of emergency for half a dozen communities and residents were evacuated and authorities put on alert for landslides and mudflows. Hundreds of people were evacuated in the suburbs of Los Angeles, with particular concerns for homes in steep-sided valleys previously affected by wildfires. 'The ground is so saturated it could move at any time', said Bob Spencer, spokesman for the Los Angeles County Department of Public Works.

Then heavy rains of up to 25 mm per hour caused a landslide on a heavily used section of Interstate 10 early on Wednesday, covering three lanes near the city of Pomona. In Highland District, 104 km east of Los Angeles, two rivers overflowed, swamping as many as 20 homes in mud. In Silverado Canyon, Orange County 25 to 30 people were evacuated from their mountain homes. 'This mudflow moved cars, picked them up, stood them up on their nose at 45-degree angles, buried them', said Bill Peters, a spokesman for the California Department of Forestry and Fire Protection.

Homes in the mountains were blocked by boulders and mud as rescue workers helped residents seek shelter. Officials ordered the evacuation of 232 homes at the bottom of large hillsides in La Canada Flintridge and La Crescenta, in the suburbs of Los Angeles.

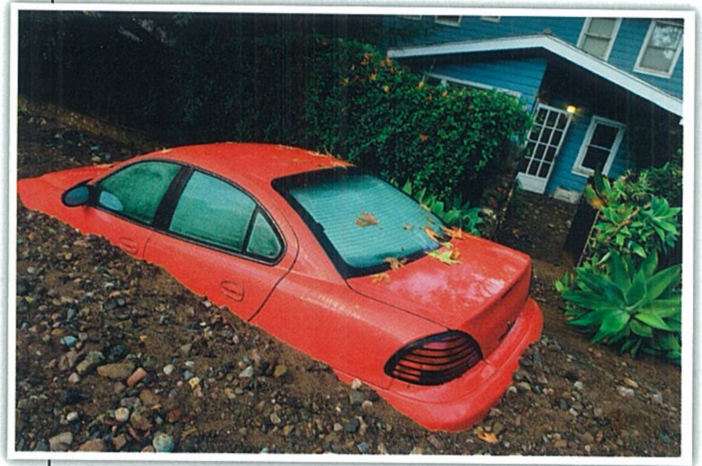


Fig. 3.45 A mudflow in Silverado Canyon, CA, December 2010

Attempts to reduce mass movement

The main method of reducing risk has been to produce maps that show past landslide features which are likely to be re-activated. This is done by the California Geological Survey. The maps indicate areas where the probability of liquefaction and earthquake-triggered landslides are significant enough to require a more detailed site evaluation prior to developments such as buildings or road construction. Before 1995 these site evaluations were voluntary but they are now a legal requirement.

A landslide inventory and related hazard zone maps are available on the California Geological Survey website. The new landslide inventory maps cover 62 square mile areas known as 'quadrangles', including parts of Burbank, Universal City, Beverly Hills, West Hollywood, Culver City and Glendale, as well as communities of Baldwin Hills and nearby View Park.

Systems such as rock bolts, netting and shotcrete are not appropriate for stabilising slopes in the soft, poorly-consolidated rocks which form many of the slopes.

Slope failures still happen frequently outside the built-up area but the system is focused on reducing the risk to property and human life where slope failures are the result of human activity.

It is difficult to produce hard statistics to evaluate the success of the system but there is little doubt that it will have had a significant effect.

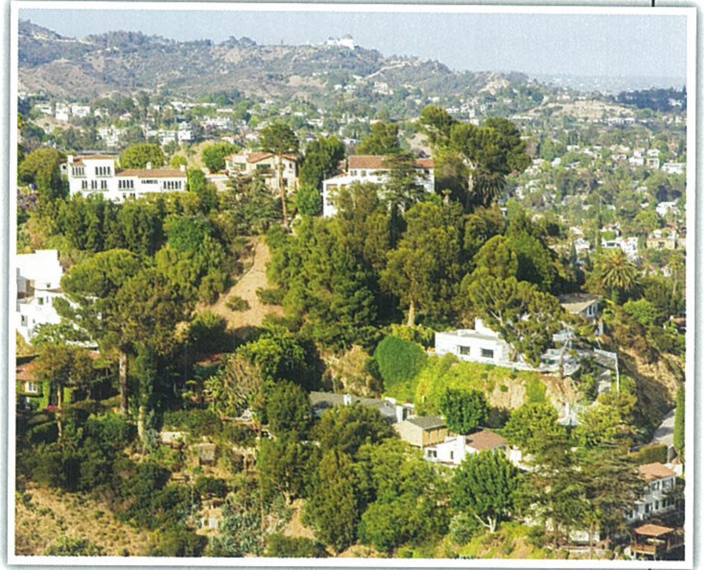


Fig. 3.46 Landslide damage in the Griffith Observatory area of Los Angeles

RESEARCH Examine mass movements in California through historical accounts such as those found at: http://articles.latimes.com/keyword/landslides-los-angeles.

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 chapter shows the concept of space in the way that weathering processes act differently in different global spaces as a result of different climatic factors. The global spatial patterns of phenomena associated with global plate tectonics are discussed. Plate tectonics provide a good illustration of the concept of changing spaces, as continents move their positions and oceans open, grow, shrink and disappear. Different global spaces have different landforms depending on the plate tectonic situation and the operating weathering processes.

Scale: this chapter shows the importance of the time scale in interpreting change from the geological past to future scenarios. Plate tectonics show how small changes over a long time scale result in the global landforms we see today. The California Geological Survey maps past slope failures which may be re-activated at some point in the future. This chapter also illustrates the importance of spatial scale. Slope processes can operate on very long time scales, e.g. creep, or very short time scales, e.g. flows, slides and falls. The chemical weathering processes operate at a molecular spatial scale yet result in large scale landform development.

Place: distinctive landforms resulting from the processes of weathering, or plate tectonics or on slopes occur in similar places in different continents. Island arcs form where oceanic plates converge wherever that place is on the globe. Granite weathers in a particular climate in the same way wherever that place happens to be on the globe. This chapter shows how widely separated places can have great similarities.

Environment: interactions between people and their environment create the need for environmental management, particularly of slope processes. Human activity is one of the key factors that can trigger slope failures which, in turn, can lead to loss of life. Building projects can lead to slope instability but measures can be taken to stabilise slopes. The last section of this chapter and the California case study demonstrate this.

Interdependence: understanding the interactions between humans and slope processes is important in knowing how particular building projects can be managed. The systems operating on slopes show how the complex nature of interacting physical processes and human activities can lead to slope failures but, once these interactions are understood, measures can be taken to prevent slope failures and to ensure human safety.

Diversity: the range of landscapes produced by plate tectonics is diverse: from fold mountains, to ocean basins, ocean trenches, island arcs and oceanic ridges. Weathering processes differ greatly in different climates and with different rock types. Slope processes differ on different slope angles and in different geological situations.

Change: the key point of plate tectonic theory is that the Earth's surface is in a state of constant change. Plates are generally moving at rates between 1 and 10 cm per year but these small movements produce the major features of the Earth's surface. Weathering and slope processes are similar in that they show how slow changes over long time periods can have major effects on the landscape. Weathering has a low magnitude and high frequency but a slope failure has high magnitude and lower frequency.

Exam-style questions

1 Study Fig. 3.47 which shows a cross-section through a road cutting.

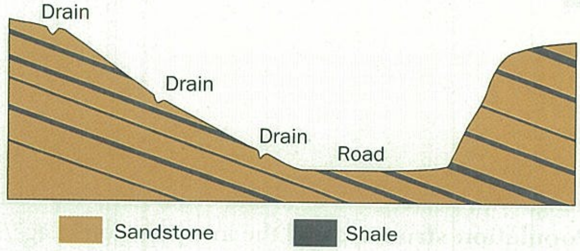


Fig. 3.47 A cross-section through a road cutting

(a) Explain why the left side of the cutting is more liable to slope failure than the right side. [3]

(b) Explain how the cutting has been designed to reduce the risk of slope failure. [3]

(c) Describe the process of soil creep and explain how it takes place on slopes. [4]

2 (a) Describe the process of sea floor spreading. [7]

(b) With the help of a diagram, explain the formation of landforms at the convergent plate margin formed by the meeting of an oceanic plate and a continental plate. [8]

(c) Why are some of the world's oceans shrinking but others are expanding? [15]