UNIT 1
Landforms and landscapes

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1

Landscapes and their landforms

Source 1.1 Australia has many striking landscapes, including The Breakaways, Coober Pedy, South Australia.

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Before you start

Main focus

The Earth is made up of many different types of landscapes and their distinctive landform features. Large-scale plate tectonic movement of continents affects landforms at a variety of scales.

Why it's relevant today

Plate movements produce mountain-building, earthquakes, volcanic activity and tsunamis, which all impact directly and often adversely on people.

Inquiry questions

- What are the different types of landscapes and landforms?
- What is the significance of plate movements for volcanic activity?
- What kinds of landforms develop from plate movements?
- Do different rocks produce different landforms?
- How do plate movements impact on people?

Key terms

- Convergent boundaries
- Divergent boundaries
- Hotspots
- Igneous rocks
- Landforms
- Lithosphere
- Metamorphic rocks
- Plate tectonics
- Sedimentary rocks
- Subduction boundaries
- Transform boundaries
- Volcanoes

Let's begin

Some changes on the Earth's surface take place slowly over long periods of time as the result of continental movements, plate tectonics and erosive processes. Other events linked to plate tectonics, like earthquakes and volcanic activity, can happen quickly. In the process, these events cause major and dramatic changes to landforms. Different rock types in the lithosphere often have different landforms associated with them.

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1.1 Types of landscapes and landforms

landform a naturally formed feature on the Earth's surface, having a characteristic shape or form

landscape the visible features of an area including both the natural (mountains, forests, rivers etc) and human elements (roads, houses, bridges etc)

riverine associated with rivers

arid dry or parched, refers to regions such as deserts

karst limestone region where underground water is the main cause of distinctive landforms

Landforms of varying sizes and shapes, when taken together, are referred to as a **landscape**. There are many different types of landscapes, including but not limited to:

- coastal landscapes
- **riverine** landscapes
- **arid** landscapes
- mountain landscapes
- **karst** landscapes.

The landforms have relationships with each other, which means they form distinctive groupings in these different landscapes. In downstream riverine landscapes, for example, landforms will include a **channel**, possibly a **levee**, and a **flood plain** or **terrace**. Some landforms are extensive, like arid zone dunes that continue for many kilometres. When numerous dunes have formed, as in the Arabian Peninsula or Central Australia, they make up a dune field that can extend for hundreds of kilometres. Other landforms are small, such as individual pedestal rocks that may be shaped like an anvil or mushroom, and reach only a metre or so in height. Geographers and others try to explain these differences in size, shape and grouping of landforms.

channel the hollowed-out path formed by a river or stream

levee a sediment embankment bordering a channel

flood plain low-lying ground that is subject to flooding from a nearby river

terrace a 'platform' of fairly flat land, often a former flood plain that has become stranded by later down-cutting by the river

Source 1.2 Sand dunes near Liwa oasis, the Empty Quarter, Abu Dhabi, United Arab Emirates

Source 1.3 Ripples in sand preserved in rock at Kings Canyon, Northern Territory, Australia

The processes that produce landforms are both large and small in scale. At a large scale, the Earth's surface is influenced by forces that affect the distribution and nature of continents and oceans. The solid continents and sub-oceanic floors provide the raw materials for other kinds of processes to act on and change. The Earth's entire surface, whether exposed as landmasses or lying beneath the ocean, is affected by **erosion**, **deposition** and **weathering**. When considering landforms, we are viewing features that have evolved over time in response to different forces acting on them.

erosion the process of transferring rocks, sediment or solutions (transportation) from one place to another (deposition)

deposition the last stage of the erosion process, when the material being moved stops and settles on a surface

weathering the breakdown of rocks and sediments into smaller particles or a solution

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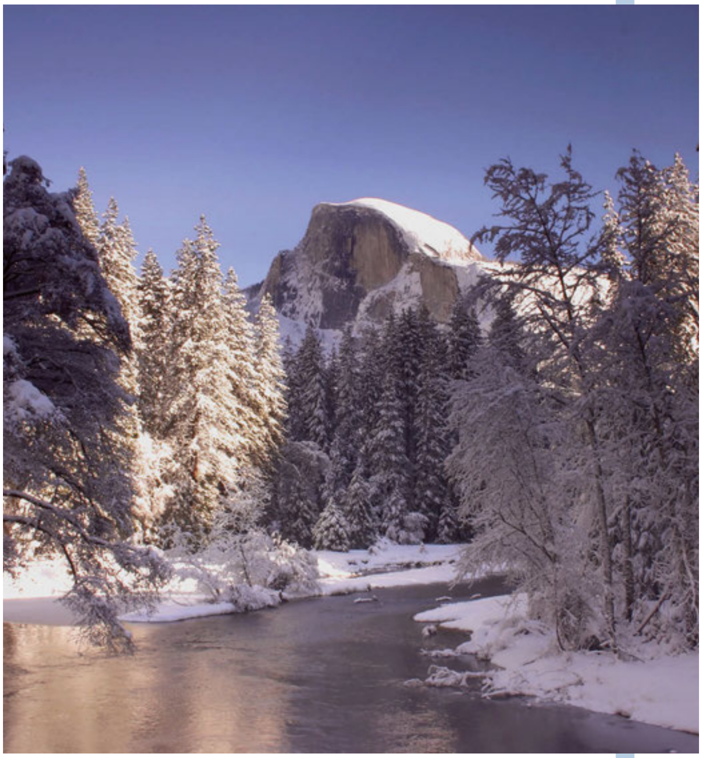
Case study 1.1

Iconic landscapes in Australia and the world

Iconic landscapes are those that are most famous and popular. In some instances, a particular dominating feature within the landscape makes it 'iconic', like Uluru in the arid landscape of Central Australia or Half Dome in the glaciated landscape of Yosemite National Park in the United States. Other iconic landscapes cover larger areas, such as the Grand Canyon in the United States or the gorges along the Yangtze River in China.

1. Research some iconic landscapes and create a top 10 list.
2. Locate these landscapes on a virtual map. You will find a link to Google Earth at www.cambridge.edu.au/geography8weblinks and you can download the software if you do not already have it.
3. Describe what makes these landscapes iconic.



Source 1.4 Half Dome in the glaciated landscape of Yosemite National Park, United States

ACTIVITY 1.1

1. Describe the difference between a landform and a landscape.
2. List the types of landforms found in riverine landscapes.
3. Select another type of landscape (for example, a coastal or arid landscape) and list the types of landforms you may find.

RESEARCH 1.1

Research online illustrations showing different landforms to create a labelled 3D model or annotated sketch of a landscape that contains a number of different landforms. Materials you could use to make a model include paper, cardboard, sand, rocks, paint, toothpicks – be creative! Compare your model or sketch with the rest of the class and evaluate its accuracy.

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Studying landforms

Physical geographers examine the **lithosphere**, biosphere, atmosphere and hydrosphere. In relation to the lithosphere, the field of **geomorphology** concentrates on the surface features of the Earth, examining landforms and the processes that have produced them. Some of these visible features are formed rapidly while others develop only over long periods of time. A large river system like the Murray-Darling may have existed for millions of years, for example, but a smaller cut-off meander or billabong along the stream can form quickly during a flood.

lithosphere the solid upper zone of the Earth, including soil and underlying rocks to a depth varying between about 7 and 200 km

geomorphology the study of landscapes and landforms, and the processes that have made them the way they are

Rocks and weathered materials near the Earth's surface are often referred to by the general term **lithology** (*lithos* is the Greek word for rock). As landform development results from processes operating on both rocks and weathered materials, these lithologies influence how effective the processes can be and how long they take before particular landforms appear. Some ancient **sedimentary** and **metamorphic rocks** may be up to 4 billion years old, allowing for surface processes of change to have operated for a long time. Other rocks are forming today and have only been exposed to weathering processes for geologically short periods. For example, volcanoes are still creating rocks by producing lava that solidifies and, although some weathered sediments may be hundreds or tens of thousands of years old, current processes are contributing to their further breakdown. In some cases, weathering processes involve solutions that may be removed from the weathered rock or cause compaction (or lithification) of sediments.

lithology the general physical characteristics of rocks

sedimentary rocks rocks formed from sediments that have later been welded or pressed together

metamorphic rocks igneous or sedimentary rocks that have been subjected to extreme pressures or temperatures that have changed their original characteristics

Geologists examine the nature of rocks and sediments that have mainly formed over long time frames, and use laboratory tools to analyse field data and samples. These tools include scanning electron microscopes to interpret the nature and history of minerals in rocks; **uranium-thorium** and other dating techniques to determine rock and sediment ages; and computer models to analyse and visualise **plate tectonic movements** and to predict locations of economically important minerals and deposits.

uranium-thorium uranium is a radioactive element that decays to radioactive thorium at a known rate over time. The proportion of uranium to thorium thus allows people to date materials.

plate tectonic movement the movement of continental and oceanic plates of the Earth's crust

Sedimentologists interpret weathered materials in order to determine their **provenance**, the processes operating to produce or change sediments, and the sedimentary environments that led to the formation of sedimentary rocks. For example, old river channels can often be identified in sedimentary rocks, thereby providing information about the conditions under which the sediments were deposited before becoming compressed into rock. If streamflow is vigorous and swift, then large pebbles and boulders can be transported. Conversely, where streams are slow flowing and have low energy, mainly fine sediments like clays and silts will be deposited. Other sediments have been laid down on the ocean floor, and these often contain remnants of broken shells or marine organisms, which provide clues to the sediments' origins.

provenance the source rock or sediment of a weathered material

Physical geographers and sedimentologists are interested in the same object: the Earth's surface. In addition, geologists want to understand how the Earth itself formed and its history, especially in relation to rocks that comprise its solid components. Rocks and sediments both occur on the Earth's surface, contributing to the development of landforms. These materials act as a framework for the surface and near-surface processes of weathering, erosion and sedimentation. Combined, this broad framework and the processes acting on it produce landscapes and their landforms.

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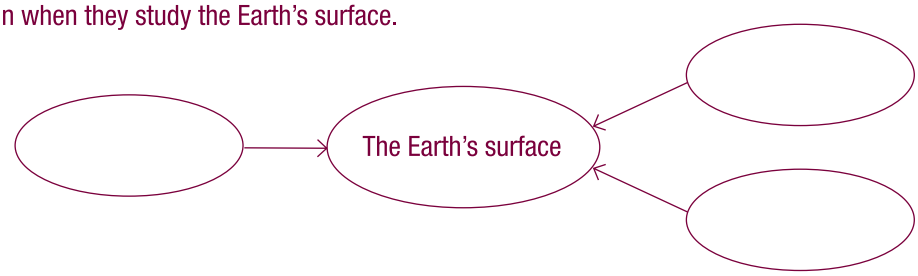
NOTE THIS DOWN

Copy the graphic organiser below and summarise the groups of people interested in landforms. Describe the different interests of each group of people. Then provide an example of what the members of each group are interested in when they study the Earth's surface.



Landforms at different scales

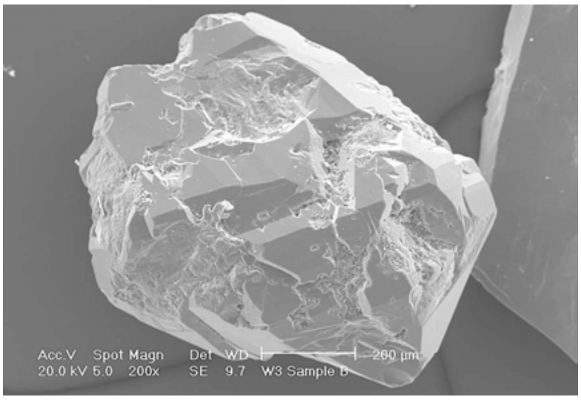
Landforms comprise the landmass and submarine parts of the Earth's surface, and contribute to a sequence of features that can be viewed at different scales. Starting at the smallest scale, weathering environments such as arid, coastal or glacial will produce different patterns on the surfaces of **quartz** grains. These grains can be examined using an electron microscope to determine probable past environments that have affected them. At the next scale, weathering features like **honeycombing** may occur on cliffed shorelines or in saline arid environments, or a stream may contain rounded gravels. Individual quartz grains of less than 2 mm diameter will be classed as small scale, moving to a sequence of larger features like honeycomb weathering at several centimetres in size, to cliffs (landforms) that may be many metres in size, and then to groups of landforms (cliffs, beaches) that make up landscapes (e.g. coastal). Landforms can also be considered at a continental scale, at which point they will be referred to as **physiographic or geomorphic regions**. Some physiographic regions in Australia would in-clude mountain chains, shield (plateau) areas and dune fields. At this large scale, there are different landforms and landscapes that contribute to the nature of continental surfaces. At the even larger global scale, continents and oceans together make up the Earth's surface. We will now examine the Earth at this very large global scale, and show how changes at this scale affect landforms at smaller scales.

quartz rock composed of silicon dioxide; a hard mineral that resists weathering

honeycombing a network of pits several centimetres deep that looks as if bees have made a honeycomb in rock

physiographic or geomorphic region an area of the Earth's surface with similar landforms and topography

Source 1.5 Honeycombing in sandstone, Sydney region



Source 1.6 Scanning electron microscope image of a river-worked quartz grain from the Hawkesbury River, New South Wales

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ACTIVITY 1.2

1 The table below is a sequence of features at different geomorphic scales. Add in 2 examples at the landscape, landform and weathering feature scales.

Geomorphic feature	Example	Two additional examples
Continent	Australia	
Landscape	Coastal	
Landform	Dune	
Weathering feature	Honeycomb weathering	
Quartz grain	In coastal dunes	
Clay mineral	In weathered rock	

2 Create a list of the landforms and weathering features that you have seen. Then research online and locate topographic maps that show some of these different landforms. Compare your list and maps with those of others in the class.

3 Identify the landform and weathering features that appear in more than one landscape type. (For example, does honeycomb weathering occur only in coastal landscapes?) Discuss possible reasons why a landform or weathering feature may be present in more than one landscape type.

Starting at the large spatial scale of the Earth's framework, the distribution of continents and oceans needs to be viewed over long timespans (large temporal scales). Crystals that have been dated to more than 4000 million years old have been found in rocks younger than those in Western Australia. The oldest rock, also around 4000 million years old, has been identified in a relatively stable area in Canada. So why are some of these rocks, thought to be present at the time when the Earth came into being, so much older than many others on Earth? We know that in places where volcanoes are active today, lava can solidify into rock. Other rocks have formed at different stages throughout the long geological time of Earth's history. This suggests that environments have changed over time and that particular events like volcanism may be intermittent. Let us start by considering the Earth's mainly solid framework over large space and large time, before examining how this affects present-day global patterns of mountains and volcanoes.

The Earth's composition

Our knowledge of the Earth's composition has been gained mainly through studying earthquakes and the **seismic waves** they produce. Although the maximum depth at which an earthquake has been detected is about 800 km, energy waves from earthquakes extend out through the Earth. These waves and the rates at which they travel can be interpreted from multiple recording stations on the Earth's surface, allowing scientists to work out which zones are solid and which are fluid or plastic, and the probable types of minerals found in each zone.

seismic waves shock or energy waves caused by earth movements

The rocks and solid materials of the Earth's surface are together referred to as the lithosphere. The upper part of the lithosphere, the Earth's crust, extends down about 40 to 80 km under the continents, but thins to about 7 km under the oceans. The crust is referred to as **sial** because it

sial crust or outer part of the Earth, forming the continents, which are mainly made up of rocks containing **si**lica and **al**uminium

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asthenosphere the plastic mantle layer below the Earth's crust, composed mainly of sima

sima the lower part of the Earth's crust on which the continental plates float, made up of rocks which contain large amounts of **si**lica and **ma**gnesium

is made up of rocks containing large amounts of silica and aluminium. Beneath the crust lies the plastic **asthenosphere**. This layer is dominated by rocks containing silicon and magnesium, and is known as **sima**. Because the crust (sial) is less dense than the mantle (sima), the crust is sometimes thought of as 'floating' on the mantle. This means that the sial of which our continents form a part has the potential to be affected by what is happening in the underlying sima of the asthenosphere. This idea is important for understanding continental movements and plate tectonics. Beneath the asthenosphere, the Earth's upper mantle extends with a transition zone to a depth of about 700 km before reaching the lower mantle at a depth of nearly 3000 km. Here the Earth's materials have high strength. This layer then gives way to the fluid outer core, which has temperatures exceeding 5500°C. At a depth of about 5100 km, there is a sharp boundary with the solid inner core. Overall, there is a gradation of mineral densities from the densest (iron and nickel) in the centre of the Earth to increasingly greater proportions of less dense minerals above the core.

Geographical fact

In 1692, the mathematician and astronomer Edmond Halley FRS (Savilian Professor of Geometry at the University of Oxford from 1702) proposed that the Earth had a shell about 800 km thick, beneath which atmosphere separated 2 concentric shells and an inner core, with all shells having light and rotating at different speeds. His 'Hollow Earth' theory resulted from attempts to explain magnetic irregularities.

ACTIVITY 1.3

1 Draw a labelled diagram of the composition of the Earth, using information provided in the text.
2 Discuss how we know the Earth is not hollow.
3 Explain why continents are sometimes described as 'floating' across the Earth's surface.

1.2 Continental drift and plate tectonics

Large-scale events can have impacts on interpreting landforms at both the continental and local levels. For example, why is there a continuous line of mountain ranges along the western margins of North and South America (the Andes and the Rockies)? At a regional scale, why are the Himalayas gradually becoming higher? In Australia, why are mountains not as high as mountains on other continents? The answers to these questions are linked to the behaviour of the Earth's crust.

The most visible part of the Earth's crust is the surface of continents. When mapping the outlines of the continents of Africa and the Americas, a Portuguese **cartographer** in the 16th century

cartographer a person who constructs and draws maps

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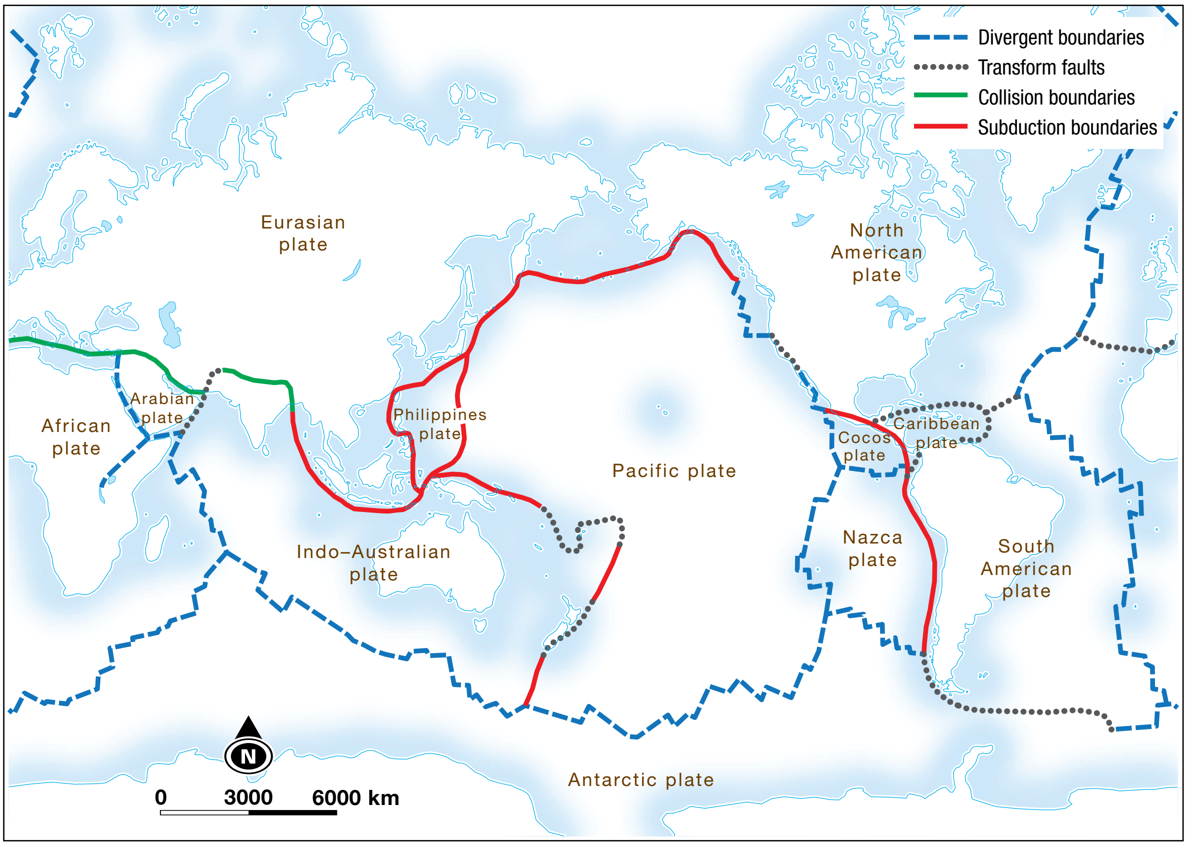
noted the shapes of these continents, and suggested that they had previously formed a single landmass. In his map of 1527, Diogo Ribeiro pointed to the complementary outlines of the western coastline of Africa and the eastern coastline of South America, which looked as though the continents had been pulled apart. This idea was considered fanciful and was ignored at the time. It was not until the early 20th century that a German scientist, Professor Alfred Lothar Wegener, pursued scientific evidence that showed fossil species in eastern America and western Africa were the same. If the notion of drifting continents was to be rejected, then the only possible explanation of the fossil evidence was the parallel development of exactly the same species in different continents, an explanation that was discounted. Subsequently, Alexander du Toit in South Africa became a strong supporter of the **continental drift theory**, and in 1937 published *Our wandering continents*. He suggested that Wegener's 'parent' landmass, called Pangaea, had existed until about 250 million years ago, when it broke into two parts: Laurasia in the Northern Hemisphere and **Gondwanaland** in the Southern Hemisphere. Additional continents came into being when these 2 landmasses were further broken up, and du Toit found more evidence of geological links between Africa and South America. The continental drift theory answered questions about global-scale fossil distributions, climate changes and landmass shapes, but the theory raised another mystery: even though it happened over a long time, what mechanism could account for huge landmasses moving about across the Earth's crust?

continental drift theory the idea that major continents may have split from a common original landmass

Gondwanaland one of two super-continents believed to have existed 510 to 180 million years ago

Knowledge about links between the continents and what is happening beneath the Earth's surface has increased dramatically over the last 30 years. We now know that the Earth's core is extremely hot, and that heat from the outer Earth is lost



Source 1.7 Tectonic plates and their boundary conditions

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conduction the molecule-by-molecule transfer of energy through a substance

convection the current-like motion of fluids in response to an uneven distribution of heat

convection plume an accumulation of hot molten rock at the boundary between the Earth's core and mantle. The molten rock then rises in a plume through a thin or fractured zone of the mantle.

through **conduction** into space. Such energy transfer from the core to space can take place by conduction or **convection**. Energy transfer through conduction is neutral in relation to landmass movement. However, when **convection plumes** develop, the energy produced is sufficient to push continents and large landmasses slowly across the crust. In other places, this energy pulls plates and landmasses apart. Landmasses at the scale of continents are then referred to as being part of around 9 major tectonic plates – for example, North America covers a large part of the North American Plate. In the case of Australia, the situation is different, as our continent forms part of the Indo-Australian Plate, which also has large areas of ocean. The entire plate is moving steadily northwards, so that the Indian peninsula is colliding with part of the Southern Eurasian Plate. The Himalayas have been formed at the boundary between these two plates.

ACTIVITY 1.4

1. Using the internet, find a map or maps showing Pangaea, Laurasia and Gondwanaland. Do the outlines of present-day continents support the idea that Gondwanaland split up into different continents, including Australia? (For maps showing continental fit between Africa and South America, you could use Google and query 'continental fit between Africa and South America'.)
2. Describe the evidence proposed to support arguments for continental drift.
3. Explain why notions of continental drift were rejected for a long time before being accepted.

Plate movements

divergent plate boundaries the point where plates are pulled apart, allowing molten rock to emerge at the Earth's surface

collision plate boundary the point where two plates of similar strength or speed collide

convergent (subduction) plate boundary the point where two plates are moving towards each other and collide, with one plate being pushed beneath the other; the lower plate is the 'subducted' plate

transform plate boundary the point where 2 plates slide, grate or jerk past one another

Tectonic plate movements occur both on continents and on ocean floors. By investigating patterns of volcanic activity and the absolute amount of continental movement over a number of years, scientists have proposed that plates are moving in different pathways and at different rates. Some plate boundary locations and movements are unclear, and these are referred to as plate boundary zones. Different landforms are associated with different kinds of plate boundary, giving clues to the way plates are behaving. The main plate boundary types are described as **divergent**, **collision**, **convergent (subduction)** or **transform**. These will be described along with their effects on landforms.

Divergent plate boundaries

seafloor spreading the separation of tectonic plates on the floor of the ocean which allows molten rock to emerge and form new ocean floors and mountains, such as the Mid-Atlantic Ridge

Here plates are being pulled apart and new rocks of volcanic origin are emerging in these spreading zones. It is thought that convection plumes exist below the spreading zones, generating both the energy for plate movement and the volcanic activity associated with it. Per-haps unexpectedly, plates that move apart do not always leave depressions or gaps in the Earth's crust. When plates diverge beneath oceans, the movement is referred to as **seafloor spreading**, and it allows for the release of molten magma,

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which generates substantial submarine volcanic activity. It is the continued outpourings of lava and volcanic rocks that lead to the formation of major oceanic ridges like the Mid-Atlantic Ridge, which extends for thousands of kilometres. Although the rate of seafloor spreading in the Atlantic seems small – about 2.5 cm/year – over millions of years the plates have moved many kilometres. The Mid-Atlantic Ridge goes through Iceland, where the North American Plate and the Eurasian Plate are moving apart, and active volcanoes follow these plate boundaries, producing dramatic scenes of hot lava encountering ice. On land, major spreading has resulted in the development of the African Rift Valley, with its associated lines of volcanic activity. The Red Sea has also been formed by diverging plates.

Source 1.8 Volcanic ash cloud, Iceland, 2010 eruptions

Source 1.9 Volcanic fissure marked by volcanic cones, Iceland

Collision plate boundaries

These boundaries occur when plates are moving towards one another, resulting in the plates colliding. Even though plates are moving slowly, they often adjust quickly, causing earthquakes. If the plates have approximately the same rock density, the collision forces parts of the landmasses upwards. This has happened in the Himalayas, where the Indo-Australian Plate is moving northwards and the Eurasian Plate is moving southwards. Scientists believe that India has moved about 6400 km northwards over the last 80 million years, colliding with Asia between about 20 and 40 million years ago. This collision has caused the Indian landmass to slow down to about half its previous rate of movement, but the collision of continental plates moving head-on into each other has created large compression stresses in both landmasses. Although some stress was relieved by upward movement of the plate edges that formed the Himalayas, the remaining and continuously developing additional stresses continue to cause numerous earthquakes. The Himalayas are still rising at a rate of around 1 cm per year and its highest mountain, Mt Everest, currently reaches nearly 9 km (8854 m) above sea-level. At present rates of uplift, Mt Everest will gain another metre in height over the next century. The **strongly folded** European Alps mark the continental collision between the western boundary of the Eurasian Plate and the northern margins of the African Plate. Countries

strongly folded squeezed into sharp folds as a result of great horizontal pressure

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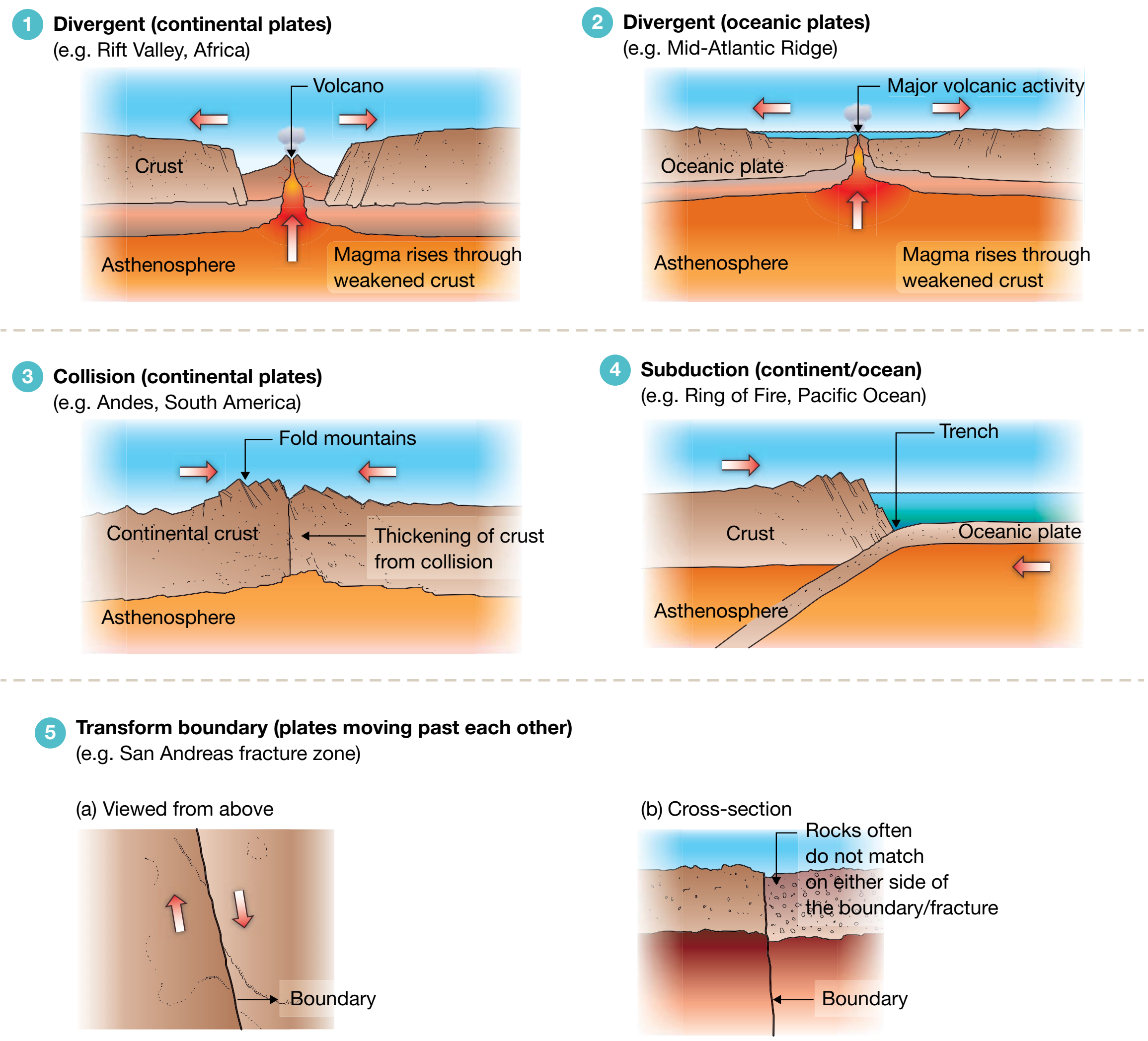
Geographical fact

People are not good at forecasting particular earthquakes, but toads may be able to assist. Five days before the L'Aquila earthquake in Italy in 2009, toads abandoned breeding sites and did not resume normal behaviour until several days after the earthquake.

around the Mediterranean thus experience earthquake activity. The ocean boundary between the Indo-Australian Plate and the Pacific Plate lies to the east of Australia, and here the Pacific Plate is moving at a rate of about 10.5 cm annually. In other places where plates are colliding beneath the ocean, deep trenches are formed as part of a subduction process.

Convergent (subduction) plate boundaries

Convergent boundaries occur when 2 plates move towards each other and one is forced beneath (or subducted under) the other. Convergent boundaries often behave differently from the collision responses of 2 land masses. Continental



Source 1.10 Divergent/collision/subducting/transform plate boundaries

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plates are less dense than oceanic plates; some oceanic plates may be denser than others; and plates may also be moving at different rates. Under these circumstances of plate differences, a process of subduction occurs in which one plate is pushed beneath the other. This can result in deep trenches being formed as the subducting plate is dragged beneath the stronger plate. Where the faster-moving oceanic Pacific Plate collides with the slower-moving oceanic Philippines Plate, the Marianas Trench reaches a depth of nearly 11 km.

The convergent boundary of the Eurasian Plate and the Indo-Australian Plate lies along an arc to the west of Java, and it was adjustment between plates along this subduction trench that resulted in the major earthquake and catastrophic Indian Ocean tsunami on Boxing Day 2004. Stresses that had been built up through continuing subduction were released suddenly by the rock moving along fractures, creating tsunamis that produced major loss of life in Indonesia, Thailand, Sri Lanka and India.

Geographical fact

Not all tsunamis are caused by earthquakes. In 563 CE, a tsunami wave between 3 m and 8 m high inundated the shores of Lake Geneva, Switzerland. Triggered by a massive rockfall, the tsunami pushed river sediments into the lake, resulting in a sudden rise in lake levels, flooding and loss of life. Currently, at least 1 million people live within the area flooded by the 563 CE tsunami.

Ocean–ocean convergence boundaries are often marked by lines of submarine volcanoes, which may eventually emerge from the ocean as islands. As the ages of volcanic rocks can be determined, the direction of movement of plates can be confirmed by the relative ages of the ocean's volcanic rocks. The oldest volcanoes represent the earliest positions of the plates, while the youngest volcanoes being those under which the plates have moved most recently.

ocean–ocean convergence boundary point where two oceanic plates move towards each other and one is pushed beneath the other

Subduction is common at continental–oceanic plate boundaries. The western boundary of the continental South American Plate (less dense) encounters the oceanic Nazca Plate (denser) and is being subducted under the landmass. In the process, the edge of the landmass is being lifted by the oceanic plate and the Andes have been formed. However, the edge of the oceanic Nazca Plate is not moving smoothly beneath the landmass, resulting in a buildup of stresses that cause earthquakes when the plates readjust.

Geographical fact

Earthquakes and tsunamis often destroy electricity grids, so how to recharge a mobile? Following the magnitude 9.0 earthquake and tsunami in Japan in 2011, the Japanese company TES NewEnergy invented a relatively low-cost saucepan-like device that allows people to boil water over a fire and recharge their mobiles at the same time.

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Transform plate boundaries

transform plate boundary the point where two plates slide, grate or jerk past one another

shear stresses stresses caused by two objects moving at an angle to each other

Transform plate boundaries are those where plates move horizontally past each other without colliding. However, plates do not glide past one another – their edges fracture and large-scale broken parts of the crust grate and grind against each other, generating large **shear stresses**. These boundaries have numerous faults or fracture zones; they often occur on the ocean floor and result in relatively shallow earthquakes compared with the deep earthquakes along collision boundaries. Of the transform fault boundaries found on landmasses, the San Andreas Fault zone in the western United States is probably the best known. It extends for more than 1000 km, and in places is tens of kilometres wide. At an average annual rate of movement of around 5 cm, the plates are moving relatively quickly past each other. The fault zone connects two divergent plate boundaries, one to the north and the other to the south. Because San Francisco is located on this extensive fault system, it suffered major collapse of buildings, loss of life and a huge fire in the early 20th century.

Geographical fact

In April 1906, a magnitude 8.3 earthquake struck along the San Andreas Fault zone. The rupture, which extended for nearly 480 km, moved at estimated speeds of about 2.7 km/s (or more than 9000 km/hr). Violent shaking for up to 1 minute had more severe effects in areas underlaid by sediments, like reclaimed parts of San Francisco Bay, than it did over bedrock. The San Francisco quake was associated with **offsets** of up to 6.4 m, which were shown by movement in fences, lines of trees, roads and rail lines. Vertical displacement reached up to 0.9 m. Both movements caused major disruption not only to buildings but also to water and gas pipelines, telegraph lines and power lines. When escaping gas ignited, water was not available to fight the fires, which raged for 3 days after the quake. Altogether around 28 000 buildings were destroyed, 87% of them wooden structures. The death toll is estimated to have been around 3000 in San Francisco itself, where 225 000 people of a total population of 400 000 were left homeless.

offsets horizontal displacements

Source 1.11 Damage to buildings in San Francisco after the 1906 earthquake

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Buildings on sediments are very susceptible to earthquake damage, as later confirmed in 1985 in Mexico City (built on lake-bed sediments) and in 1989 in Newcastle, New South Wales (built on river-deposited sediment). Photos of the San Francisco earthquake can be found at www.cambridge.edu.au/geography8weblinks.

Australia and plate tectonics

Unlike other continents, the Australian landmass has not been subjected to major collision or transform plate boundary conditions. This means that we do not have an equivalent of the Rockies, the Andes, the European Alps or the Himalayas, or high mountains like Mt Kilimanjaro in Africa (5895 m). The Tasman Sea between Australia and New Zealand formed after divergence of the 2 landmasses and later the Great Dividing Range was uplifted. Over geological time, the range has been eroded down to a maximum height of 2230 m at Mt Kosciuszko. The Great Dividing Range extends for about 3500 km along the east coast of Australia, and now acts as a watershed dividing the west-flowing rivers towards the inland from the shorter coastal rivers flowing to the east.

ACTIVITY 1.5

1 In your own words, describe the 4 main plate boundary types.
2 Explain why collision boundaries between 2 continental plates behave differently from convergence between 2 oceanic plates.
3 Identify the types of plate boundaries most often associated with earthquakes.

NOTE THIS DOWN

Copy the graphic organiser below and give an example of each boundary type and associated landforms.

Nature of plate boundary	Example (location)	Landform/s
Collision	Himalayas	High mountains
Divergent		
Convergent (subduction)		
Transform		

RESEARCH 1.2

In groups, select 1 of the major continental or oceanic plates and use the internet to gather information about the rate and direction of its movement. Assess what the likely outcomes of this movement will be over the next century, and share your results with the class in the form of a PowerPoint presentation.

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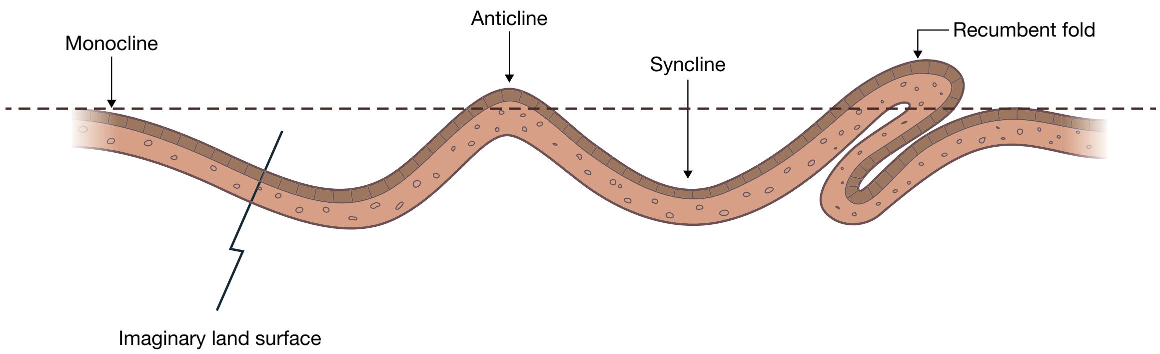
Rocks responding to pressure

The Earth's surface is capable of being deformed or bent slightly (a process that is called plastic deformation, or rock elasticity) but relative to materials underlying the crust, it is rigid and brittle. This means that stresses can be applied in a particular place without the surface rock breaking immediately. However, if stresses continue to build up, they eventually will cause the crust to fracture and sometimes to bend. These large-scale outcomes of earth forces are referred to as tectonic landforms, and are produced by faulting and folding. Evidence for tectonic landforms is most obvious and lasts the longest when the affected rocks are very resistant to weathering and erosion.

Folding

When plates collide or converge, the edges of some continents are forced upwards and mountains are formed. This process usually causes large fractures in the crust and occasional rapid movements to release the built-up stresses. The readjustment of the stress load affects rocks at the surface. Any lateral or sideways pressure (compression) can result in rocks being squeezed and then responding to this stress by buckling. Rocks formed from sediments being deposited in layers or beds (sedimentary rocks) and layered rocks that have been subjected to extreme pressure following their formation (metamorphic rocks) can both respond by buckling or folding.



Source 1.12 Different fold types

The main kinds of folds are anticlines, synclines, monoclines and recumbent folds.

anticline the upward bulging of rocks caused by compression

syncline the downward squeezing of rocks caused by compression

Anticlines and **synclines** are often associated with one another. Anticlines are beds that have been forced upwards, producing an upward bulging of rocks and a convex upward shape at the surface. The syncline represents the nearby rocks that have been squeezed downwards (convex downward shape). Even though the rocks have been distorted, the oldest layer remains in the centre or lowest point of the anticline. Because the formation of an anticline involves stretching of rocks at the top of the bulge, additional cracks often appear usually at right angles to the bedding layers. This means that the higher parts of the anticline are the most fractured and vulnerable to weathering and erosion. In the field, younger fractured rocks on the former crest of an anticline may be eroded away, leaving younger rocks on the flanks and older underlying rocks remaining at the centre of the anticline.

The reverse of this is the syncline, which represents a convex downward fold. In the centre or lowest point of the syncline lies a zone of compressed rocks, which are more resistant to forces of weathering and erosion. Over long periods of time the fractured anticlinal bulges

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Source 1.13 Wilpena Pound, South Australia, an eroded syncline: the basin shape represents the centre of the syncline where rocks have been compressed.

will be weathered and eroded down, leaving the synclinal part of the fold system as the highest point in the landscape. Wilpena Pound in the Flinders Ranges of South Australia is an eroded syncline.

Sometimes folding results in only gentle buckling of terrain over extensive areas, as occurs in south-western Queensland and nearby parts of New South Wales and South Australia. Erosion of a gently folded ancient silcrete surface in these areas has left many remnants of ancient folds but no crests of anticlines.

Monoclines can be formed by fault movements at depth and may be gentle folds without steeply inclined layers. The Lapstone Monocline marks the eastern margin of the Blue Mountains near Sydney, and has numerous faults associated with it. This combination of folding and faulting is logical, as both structures require major forces for their development, and frequently the continental forces applied exceed rock strength, leading to buckling and/or fracture. In Western Australia, a major monocline now stands at about 850 m above the surrounding plain, approximately 860 km north of Perth. This large isolated outcrop, called Mt Augustus, extends for about 8 km and is made up of rocks that could be 1000 million years old. Beneath these ancient sediments is even older granite that probably solidified about 1650 million years ago.

monocline a simple fold that occurs singly rather than as part of a series of anticlines and synclines

Recumbent folds are those that have folded over themselves or overturned ('reclining'), so that initially the youngest rocks are on the surface. When the fold is eroded, older rocks beneath the

recumbent folds those that have folded over themselves or appear to have flopped over

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original upper layer become exposed. In this way, the sequence of rock ages is not the normal one of youngest at the top and oldest at the bottom, but a sequence of older–younger–older. Careful investigation of folded rocks is needed to ensure that the relative ages of landforms developed on them are not misinterpreted. In recumbent folds, the axial direction of the fold is approximately parallel to the bedding planes. Recumbent folds are frequent in strongly folded terrains like the European Alps.

Fold mountains

Folding is often accompanied by uplift, so that fold mountains are relatively common. Many mountain ranges have folded rocks, and this shows that they have been subjected to compression or shear pressure. All the folded mountain ranges in Australia also have **faults** present, and sometimes the ranges are marked by an **escarpment**. Compared with the high mountains making up the European Alps, the Himalayas, the Andes and the Rockies, Australia's fold mountains are much more subdued. To the east of Adelaide, the Mt Lofty Ranges – sometimes referred to in texts as 'a series of hills' – rise to a height of 727 m, and have been subjected to both folding and faulting. Folding is also present in metamorphosed and folded rocks around Brisbane, but the main range to the west is composed of a series of volcanic flows.

faults fractures in rocks or sediments where movement has occurred as a result of compression or shear stress

escarpment a sharp and continuous break in slope that may extend for hundreds of kilometres

ACTIVITY 1.6

1. Sketch an anticline, a syncline, a monocline and a recumbent fold.
2. Use the internet to find the locations of 2 examples of each type of fold.
3. Sediments are deposited over time, so the oldest sediments are laid down first and younger sediments are deposited on top. Explain how older beds can sometimes be exposed with younger strata beneath them.

Faulting

curvilinear in a curved line when viewed from above

Faults are linear or **curvilinear** fractures that may be approximately vertical, or be angled towards the surface, and often more than one fault is present. Where rocks have been subjected to compression, folding or uplift, or where shear stresses have developed, faults of diverse lengths may form to relieve the stress. In some cases, a series of fractures (faults) will occur within metres or kilometres of one another, as happens in the Mt Lofty Ranges. Other fault lines have eroded into major landforms, such as the Darling Fault to the east of Perth, which extends as a fault line escarpment for about 1000 km. Because the relatively uplifted side of any such fracture has been eroded over long periods of time, often faults may now be located at some distance from an escarpment, rather than at the junction between the higher and lower land surfaces.

Faults are not always associated with folding or compression. Where plates are diverging, large-scale fractures or faults develop. The Rift Valley in Africa has formed from plates diverging and the land between them becoming lower than that on either side. A string of active volcanoes has developed along the fault lines, marking the boundary between relative uplift and subsidence. This situation of fault lines separating higher from lower ground is referred to as a **block fault**, because the land in such areas tends to move as cohesive large chunks or blocks. At a much smaller scale, the Mt Lofty Ranges represent a block-faulted range, bounded by faults on both sides, with additional

block fault large area of land upthrust by earthquake activity

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Geographical fact

Faults or fracture lines can develop while people are watching. In 1968 at Meckering, 130 km east of Perth, a 6.9 magnitude earthquake created a rupture 37 km long. The **earthquake focus** was shallow – about 7 km, compared with about 30 km for the Japan earthquake in 2011. At Meckering, railway lines buckled, the ground moved visibly in waves or bumps, numerous fractures opened to about 5 cm and then closed, and sudden changes in land surface elevation were noted. Eyewitness accounts include that of a driver who saw 'immediately in front of him a 2.5 m high bump [rising] in the road where 2 seconds before none had existed'. Another observer, travelling in the opposite direction along the Great Eastern Highway, 'felt the shaking and saw the scarp rise, and crashed into a tree at the roadside, breaking an arm'. General vertical displacement along the new fault scarp was 1.5 m.

earthquake focus depth where rupture from an earthquake occurs

horst a chunk of fault-bounded land that is higher than the land on either side

graben a chunk of fault-bounded land that is lower than the land on either side

faults and associated 'blocks' between them. Where fault-bounded land is relatively uplifted rather than down-faulted (as in the Rift Valley), the uplifted block is referred to as a **horst**. A down-faulted block is called a **graben**. Spencer Gulf and Gulf St Vincent in South Australia are both submerged grabens.

In the western United States, an extensive area of faulting has produced alternately uplifted and down-dropped country. Probably more than 15 million years ago, the Basin and Range region of the Cordilleras started to form as a result of crustal stretching. The outcome is a series of roughly parallel uplifted (mountains) and down-dropped (valley) areas where the height difference (relief amplitude) between valleys and mountains can be more than 3000 m. Faults are angled so that peaks alternate with valleys. Volcanic activity has resulted from weaknesses created by crustal movements and fracturing. The geologist Clarence Dutton in

Source 1.14 Fault line forming an escarpment in the Rift Valley, Kenya, Africa

Source 1.15 Alluvial fan deposited in front of fault-bounded mountains, Death Valley, California

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alluvial fan water-deposited sediment that spreads out into a fan shape when viewed from above

ephemeral drainage drainage lines without permanent water flow

1886 described the Cordilleras as 'coming up through Mexico and crossing into United States territory … looking … like an army of caterpillars crawling northward' when reviewed on a map. Movement along the fault planes is continuing, and faults have cut through extensive **alluvial fans** deposited at the outlets of **ephemeral drainage** lines. Because the area is arid, with relatively low annual streamflow, and the uplifted country has blocked the rivers that do exist, the Great Basin area of more than 500 000 km^2 is a zone of interior drainage.

Faults can also occur in zones of plate convergence (subduction). The enormous stresses built up as a result of the Indo-Australian Plate moving north-east and overriding part of the Eurasian Plate near Sumatra were released extremely rapidly on Boxing Day 2004 by the creation of a 1300 km-long rupture, which is estimated to have travelled at speeds of about 2.8 km per second. Both horizontal (10 m) and vertical (3–4 m) movements occurred along the fault, resulting in severe earthquakes and the largest tsunami on record, in which wave heights of up to 30 m were registered.

ACTIVITY 1.7

1. Using the internet, locate an image of the Cordilleras in the western United States.
2. Describe how a feature like the Cordilleras has developed.
3. Evaluate whether the Cordilleras look like 'an army of caterpillars crawling northward', as described by the geologist Clarence Dutton.

Locating a fault

The idea of rocks fracturing under stress is easy to understand, but how would we go about finding a fault in the field? What kinds of evidence would we look for, and can the presence of a fault be inferred by assessing surface landforms?

Because faults are stress fractures and the stress may have originated from a number of directions, they can often be seen in quarries where a line of crushed and fractured rock, or **breccia**, appears. The fault zone may be seen as a single break or as a series of fractures in the quarry face and, if the rocks are layered, some of the layers will be offset by movement that occurred when the fracture formed. In other places, no quarry or cutting is available to determine the actual location of a fault line, even though sedimentary layers have been offset. These faults – the precise location of which is unclear – will be represented on geology maps as broken, rather than solid, lines and labelled as '**inferred faults**'.

breccia angular pieces of rock of various sizes that have been broken and fractured along a line as a result of fault movements

inferred fault a fault that is assumed to exist from field evidence, but that cannot be located precisely

Landforms on the Earth's surface often give clues to the presence and general location of faults. As faults represent broken or fractured rock, the zones where they occur are more susceptible to weathering and erosion than the adjacent rock. These weaker zones are often exploited by streams whose direction, when viewed from above (in plan) from maps, aerial photographs or remotely sensed imagery, will often follow fault lines. Any river with a suspiciously straight pattern needs further attention – is it following a line of weakness? Is the channel a human-constructed one, as many drainage channels are? In the Burrup Peninsula area of Western Australia, streams follow fault lines through rocky terrain, while in the south-east of South Australia numerous straight-line drainage channels have been constructed across a coastal plain.

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Larger-scale faults may involve relative uplift and associated subsidence of other land. When this happens, streams may be obstructed by land that has risen, and thus prevented from continuing on their normal path. Swampy and poorly drained ground is then created, as occurs along the Californian coast to the north of San Francisco. In this case, the disruption to drainage lines has been caused by the swarm of fractures along the San Andreas Fault belt. **Topography** there has been affected by both vertical and horizontal movements along different individual faults. When shear movement dominates along a fault line, drainage lines can be offset in the same way in which railway lines and roads develop 'kinks' if subjected to similar stress.

topography the layout of the land

Faults extend down into the earth and can affect subterranean features like **groundwater flow**. Following the Great San Francisco Earthquake, springs and artesian wells recorded changes in flow rates. Disruption to water tables in areas having saline groundwater can result in surface water becoming unexpectedly saline. In south-west Iran, a reservoir was constructed for hydroelectric power and downstream irrigation for agriculture. Water quality of the river downstream of the dam was seriously affected by salinity, which could not be explained by the nearby surface exposures of salt-bearing evaporites. As the salt-contaminated streamwater zones coincided with the fault zone, the saline surface water was attributed to the intrusion of **brackish** water through fault fractures.

groundwater flow water that moves slowly below ground through sediments and cracks in rocks

brackish containing salt levels between those of fresh water and seawater

Other fault-like fractures can be caused by human activities. In the Blue Mountains in New South Wales, underground (longwall) coal mining creates tunnels up to 3 or 4 m high and 350 m wide, extending for several kilometres. When the overburden collapses, fractures are formed and these have major impacts on both surface watercourses and groundwater movement. Some creeks normally containing rock pools no longer carry water, which instead has drained into fractured rock. Other creeks only flow following heavy rainfall, rather than year round as before, and upland swamps have become dry. Reduction in surface flow and storage has meant a transfer of water underground, sometimes flooding existing or abandoned mines, and depriving water catchments of run-off that previously would have been collected in water reservoirs.

Geographical fact

Mt St Helens started forming about 40–50 000 years ago in a fault zone to the north of San Francisco. Including the 1980 eruption, 9 major events have occurred since its formation. On a broader scale, the Pacific Plate is being subducted offshore beneath the North American Plate at a rate of about 40 mm per year. This has created earthquakes, volcanoes and tsunamis. Mt St Helens had faults before the latest eruption and rising magma increased the number of splits, forming new fault lines and creating earthquakes. As well, the magma caused the crater floor to tilt outwards, causing movement along existing fractures.

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ACTIVITY 1.8

1. Make a list of 3 landform 'clues' that can be used in the field to recognise the presence of a fault.
2. Describe how each landform 'clue' has developed.
3. Assess whether the 'clues' could be explained by processes that do not involve faults.

Joints

Unlike faults, other planes of fracture in rocks may have a fairly regular pattern, which is sometimes restricted to particular types of rocks. Those rocks that solidify from magma or molten material are called igneous rocks, and their cooling can be associated with specific fractures or joint patterns. In basalt, for example, columnar jointing or vertically oriented rock columns form, contrasting with rectangular jointing (vertical and horizontal fractures) in rocks like granite. Even though joints exist in many rocks at this local scale, they are still subject to compressional and tensional forces that can produce faulting on a larger scale.

Source 1.16 Weathering along rectangular joints in granite produces large boulders, Devil's Marbles, Northern Territory.

Source 1.17 Columnar jointing develops in basalt as it cools: near the Giant's Causeway, Northern Ireland.

1.3 Volcanism

Volcanic activity occurs along collision, convergent and divergent plate boundaries both under the oceans and on landmasses, and along fault-bounded land or sea bodies. Transform plate boundaries, where plates move past each other, generally are not associated with volcanic activity. Much of the volcanism found along convergent plate boundaries is explosive, while most volcanic activity taking place along divergent boundaries involves non-explosive outpourings of lava. As many convergent plate boundaries are on or near landmasses, explosive volcanism is what people generally experience. The 'Ring of Fire' around the Pacific Ocean represents more than 1000 volcanoes that have appeared on convergent plate boundaries. Of those volcanoes that have erupted

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during historical time, the highest is in the Andes in northern Chile, at an elevation of nearly 7000 m. There is evidence of submarine volcanism having taken place over the last 150 years at depths of about 5300 m in the Mid-Atlantic Ridge (divergent plate boundary).

Volcanoes and hotspots

In addition to converging or diverging plate locations, volcanoes can be found where plates are considered to be relatively stable, such as in Australia. The Hawaiian Islands are also located thousands of kilometres from a plate boundary. So what causes volcanic activity? In general, where the movement of continental plates allows for a thinning or weakening of the crust, molten rock can emerge as a volcano at the surface. This happens whether the thinning or weakening of the crust occurs along a plate boundary or within it. In both cases, molten rock emerges at the Earth's surface, whether on a landmass or under the ocean. However, landmass thinning in locations far from plate boundaries is a complication to the plate tectonics mechanism. A general explanation for both plate boundaries and stable within-plate locations has been proposed: namely, that all volcanoes may be the result of **hotspot activity** (or high heat energy sites). Two interesting and incompletely answered questions arise from this. First, what causes the hotspots to form? The mechanism for hotspot formation remains unknown, but in seeking the answer researchers have suggested that differences in heat energy distribution within the Earth may result in the development of convection plumes. These would be capable of forcing molten rock through the crust, especially in places of pre-existing fracture (plate boundaries), but also where the lithosphere is thinner – whether this occurs under the oceans or in a mid-plate location. Second, do the hotspots remain fixed in the same place, or do they migrate over time? The initial hypothesis proposed that convection plumes remained at fixed points, with lithospheric plates moving slowly over them. If a string of volcanoes were present along a plate boundary or within a plate, then a 'fixed' convection plume/hotspot would produce a series of volcanoes of increasingly younger ages. There is evidence of this happening in the Hawaiian Island archipelago, which is not located on plate boundaries, and where the oldest volcanoes are in the north-west and the youngest in the south-west. However, hotspots (such as in Hawaii and Iceland) do not appear to be fixed in relation to one another, so there may be more than one mechanism to explain the patterns of volcanic ages.

hotspot activity current volcanic activity associated with convection plumes

ACTIVITY 1.9

1. Using the internet, locate 2 maps showing:
   a. the Pacific 'Ring of Fire'
   b. plate movements.
2. Note the types of plate boundaries around the Ring of Fire (collision, convergent (subduction), divergent or transform).
3. Consider whether particular types of plate boundaries have caused the Ring of Fire.

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Volcanoes: active, dormant or extinct?

Volcanoes are often described in terms of their activity. Even though it seems that these descriptions are obvious and useful, when considered in detail such categorisation is not a simple matter. For example, active volcanoes can be classified as those that have produced ash, lava, pumice or gases over **historical time**. Although this seems like a sensible definition, 'historical time' covers different timespans in different parts of the world, and probably encompasses a maximum period of only about 6000 years (which is geologically insignificant). Some classifications use the combined historical **Holocene** and late **Pleistocene** periods as representing 'active' volcanoes, because radiocarbon dating methods can reliably determine ages up to about 40 000 years before the present. Dormant volcanoes are those for which we have evidence of past activity during the historical period, but that are not active now. However, volcanic activity is not always a continuous process, and a particular volcano may be intermittently active over much longer time frames. The category that has led to the fewest number of unpleasant surprises over historical time is the 'extinct' volcano, but even these volcanoes can again become active. Humans have difficulty being precise about volcanic activity due to a mismatch in time frames. We consider a few thousand years to be a long time, but attempts are being made to assess landscape features operating over geological time frames of millions or tens of millions of years. There are bound to be some erroneous evaluations, even without the added short-term problem of trying to predict when a volcano known to be 'active' will next produce dangerously massive explosions, molten rock or poisonous gases.

historical time the period during which humans have recorded events

Holocene a geological epoch characterised by the growth and impact of the human species between the present and 10 000 years ago

Pleistocene a geological epoch characterised by the formation of widespread glaciers between 10 000 and 2 million years ago

Case study 1.2

The Tambora volcano, Indonesia, 1815

In 1815, the largest volcanic eruption during historical times took place in the Flores Sea near Lombok in Indonesia. Tambora had been considered an extinct volcano until then, when approximately 50 km^3 of dense rocks were ejected. Before the eruption, Tambora stood at about 4300 m but the summit exploded, leaving a **caldera** measuring 6 km wide and 1 kilometre deep. The new summit reached only 2850 m, a collapse of nearly 1.5 km. Apart from massive **pumice** flows, the volcano ejected an estimated 60 million tonnes of sulphur – more than 6 times the amount from Pinatubo (Philippines) in 1991 – and large amounts of fluorine, which is toxic to people and livestock. The violence of the eruption sent plumes of ash up to 43 km into the atmosphere, and explosions could be heard up to 2000 km away. During the worst few days of the eruption, many places within 600 km of the volcano remained 'pitch black', and air temperatures dropped dramatically. Global temperatures may have dropped by up to 3°C.

The after-effects of the volcanic eruption were severe. Immediately following the eruption and associated earthquakes, tsunamis reached a maximum height of 4 m and inundated low-lying coastal areas. Ash build-up caused buildings to collapse and people had difficulty breathing. At least 71 000 people are estimated to have died during the eruption or immediately afterwards, when no food or uncontaminated water was

caldera large basin-shaped depression caused when the summit of a volcano collapses into the magma chamber below or explosions destroy the summit

pumice a light-coloured rock with many holes (**vesicles**) due to gases mixing with rapidly solidifying lava and trapping multiple air bubbles. Pumice is light and floats on water.

vesicles holes, often round in shape, where air bubbles were trapped in lava

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available. Up to 3 years after the eruption, pumice and tree trunks formed sea-borne rafts up to 5 km across, and posed a major hazard for shipping.

The massive quantities of ash ejected into the atmosphere had climate impacts in the Northern Hemisphere. On the positive side, sunsets and twilights in places like London were spectacular. However, the year following the eruption – 1816 – was called the 'year without a summer' in north-east North America and Europe. That year, the weather was much wetter than usual and cold temperatures shortened the growing season. Grain crops failed, potatoes rotted in the wet ground and people suffered from major outbreaks of typhus.

1. Locate the Tambora volcano on a map.
2. Identify whether the Tambora volcano lies on or near a plate boundary.
3. Assess the importance of 5 impacts of the Tambora eruption on human populations.

Geographical fact

Pumice stones were used by clothing manufacturers to produce the original stone-washed jeans.

Volcanic activity and landforms

Volcanic activity is often associated with other events – especially earthquakes, tsunamis and topographic changes – along with the release of enormous amounts of sulphur dioxide and clouds of ash into the atmosphere. Volcanic activity is complicated and variable, producing an array of different landforms. Only some of the numerous and sometimes overlapping volcanic types and **morphologies** are described here, namely composite (stratovolcano), caldera and crater, fissure vents and shield volcanoes. Other landforms include the formation of islands such as the Hawaiian Islands. Much volcanic activity in regions of known volcanism has occurred at various times in the past, with evidence of sequences of lava flows or ash deposits of different geological ages, and the presence of calderas that represent collapsed or exploding former volcanoes. An active volcano is thus always at least partly a constructional feature, as molten rock is extruded at the Earth's surface, but explosive emissions involving gas and water may destroy the tops of existing volcanoes.

morphology form and structure of shape of landforms

Composite volcanoes are those from which a number of eruptions have deposited lava, rock debris and ash in layers. Many of these volcanoes are composed of a symmetrical cone with a single central vent. Others have a central vent and additional multiple vents on their flanks, resulting in complex layering of volcanic materials. In either case, ongoing deposition from volcanic activity has to be at a rate that outstrips erosion, as some volcanic sediments are easily eroded. Mayon volcano in the Philippines has relatively frequent eruptions, which allow it to maintain its exceptional symmetry.

When volcanic activity is accompanied or followed by explosive emissions, the summit of a volcano or group of volcanoes may be blasted away, leaving a large basin called a caldera. These depressions may be up to 100 km in size, and some calderas fill with water to form a lake. One of the largest water-filled calderas is Crater Lake in Oregon in the United States, which formed about 7000 years ago following major eruptions and the collapse of existing cones. The caldera is 8 km by 10 km in size, and about 1200 m deep. Although volcanologists classify calderas and the smaller craters (<1 km in size) separately because of different origins, the landform results are similar

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Source 1.18 Types of volcanoes

Volcano type	Vent	Emission	Size of emission	Examples/ characteristics
Flood/plateau	Fractures	Very liquid lava, flat-lying basalt	Very widespread	Deccan Traps, India – basalt >2 km thick covering >500 000 km^2
Shield	Central **vent**, large, up to 7 km in size	Liquid lava – series of slow flows	Large	Mauna Loa, Hawaii – ocean floor to peak >8500 m (4169 m ASL)
Cinder cone	Central vent, often with crater at top	Explosive liquid lava, breaking to cinders	Small	Parícutin, Mexico – 1943, cone to 366 m, ash covered about 260 km^2, then quiet lava flows
Composite/ stratovolcano	Central vent, cone-shaped, fissures on flanks solidify as dykes	**Viscous** and **pyroclastic**; moves at up to 200 m/s; 350ºC to >1000ºC	Large	Mt St Helens, USA; Mt Fuji, Japan; Mt Pinatubo, Philippines (erupted 1991, previously dormant for 600 years)
Volcanic/lava dome	Central vent, often in craters, or on flanks of composite	Very viscous, can be explosive, lava builds up near vent	Small	Mont Pelée, Martinique – pyroclastic; hot ash, gas and debris at >150 km/h killing about 30 000 people
Caldera	Central vent	Collapse after explosive emissions or after long erosion	Very large	Crater Lake, USA – also called a composite volcano; Mt Warning, NSW – erosion caldera, >1 km deep, >40 km wide, extinct for 20 million years

vent opening in a volcano through which molten rock, gas and water can escape

viscous with a thick consistency that allows for flow (neither completely liquid nor solid)

pyroclastic describes a superheated mixture of rock, ash, gases and water that moves rapidly downslope as a result of a volcanic eruption

drainage basin an area of land where surface water from rain and/or melting snow and ice joins at a single point at a lower elevation another water body such as a river, lake, dam, estuary, wetland, sea or ocean

except for the size difference. Craters are formed by explosive eruptions that do not involve collapse. In Chile, the Cotopaxi crater lies at a height of about 5900 m, and has a glacier-covered rim and a **drainage basin** with ice patches. This volcano has had several violent historical eruptions, including one in 1877 when **lahars** travelled more than 100 km to the Pacific Ocean.

Shield volcanoes are those producing low-angle slopes and resulting from numerous vents that have poured out vast quantities of lava and volcanic materials over extensive areas. In Australia, the Newer Volcanics Province includes western Victoria and the extreme south-east of South Australia. Nearly 400 small volcanoes have

lahar mixture of water and rock fragments flowing down the slopes of a volcano, usually following river valleys

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Source 1.19 A water-filled caldera forming the Blue Lake, Mt Gambier, South Australia

produced a shield area of around 50 000 km², with the most recent eruptions having taken place about 5000 years ago at Mt Schank and Mt Gambier (the location of the water-filled crater of Blue Lake) in South Australia. These 2 explosive eruptions in South Australia were the culmination of volcanic activity that had begun in the Tertiary period (commencing about 65 million years ago). In India, the Deccan Traps were formed about 60 to 68 million years ago by multiple layers of **extruded** shield and flood basalts, which exceed depths of 2000 m. Due to erosion and plate movements, the flood basalt province now covers only about 500 000 km²; it was even more extensive in the geological past. Lava flows sometimes produce unusual features, like the Undara Lava Tubes in north Queensland. Here lava flowed down valleys, solidified at the surface and allowed molten lava to move out beneath the solidified surface. Once lava ceased flowing, the large underground gaps remained, creating the tubes that now form a bat habitat and attract many tourists.

extruded pushed out through a vent or fissure

Fissure vents are those where magma and gases escape through often lengthy fractures in the Earth's surface. Many of these fractures are associated with existing volcanoes, either because the magma is forcing the ground to fracture or because plate movements have ruptured the surface. In the 2 months before the 1991 eruption of Pinatubo in the Philippines, a 1.5 km long fissure was marked by steam, some ash emission and explosion craters. The fissure extended to the volcano's summit when the major eruption occurred in June of that year. Numerous fissures appear in Iceland, which is an above-sea-level part of the Mid-Atlantic Ridge, along the zone of seafloor spreading. Fissure vents in Iceland are thus probably created by divergent plate movements.

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ACTIVITY 1.10

1. Find images showing examples of 3 different types of volcanoes.
2. Indicate where the volcanoes are located and when they erupted last.
3. Discuss the impacts on human populations of the volcano types investigated.

Plate tectonics and landforms at different scales

Plate tectonics and volcanism help us to understand landform differences at the continental scale, but the results of these forces are also visible at regional and local scales. At a regional scale, basalt flows from volcanoes may extend over a subcontinent, as in India; a graben may be inundated by the ocean, as in Spencer Gulf in South Australia; or a series of volcanic islands may appear, as with the Hawaiian Islands. At the smaller local scale, swampy ground and changed river directions can result from fault movements; anticlines and synclines can be recognised in railway cuttings or other exposures; and volcanic craters of varying sizes can develop. Even smaller landform features are associated with each of the local or regional scale landforms – for example, fractures can be identified in crests of anticlines. When considering the processes at work to create landforms, each scale tends to overlap with others, so it is useful to think of possible explanations at various scales.

UNIT 1: LANDFORMS AND LANDSCAPES

1.4 Rock types and landforms

Some landforms develop mainly on one rock type, like caverns in limestone. Other landforms, such as **inselbergs** (German for 'island mountains'), can occur on a variety of different rocks. Rocks and weathered rock (sediments) can be viewed as the raw material of landscape that is fashioned into different forms by weathering and erosion. We can illustrate this by taking examples from the 3 main groups of rocks: igneous, sedimentary and metamorphic.

inselberg an isolated steep-sided hill, often made of bare rock

Igneous rocks and landforms

Igneous rocks originate from the solidification of magma. Rocks that solidify at depth are referred to as intrusive rocks, while those formed at the surface are called extrusive rocks, but various gradations exist. When magma cools slowly at depth, most crystals grow to larger than about 1 mm across, and so can be seen with the naked eye. This is the case with minerals in granite. In contrast, extrusive rocks solidify from magma that has cooled quickly at the Earth's surface. Basalt, an extrusive rock, contains small crystals and often has vesicles.

Granite is more resistant to weathering and erosion than basalt because of the minerals it contains. When basalt outcrops in a wet climate, it eventually breaks down into a fertile soil. Granite, on the other hand, weathers more slowly into a gritty infertile soil due to the amount of quartz grains it contains. If relatively resistant granite is not strongly fractured by joints, it can form isolated high outcrops like Sugarloaf Mountain in Rio de Janeiro (Brazil), Wave Rock in Western Australia and the inselbergs on Eyre Peninsula in South Australia. These rock surfaces are relatively impermeable, and in Australia have been used as water collectors. Pits (gnammas) on the inselbergs often contain water after rain, and these natural supplies were used by Aboriginal people. Subsequently European settlers used some inselbergs as water-catchment areas for local dams.

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Source 1.20 Wave Rock, a granite inselberg at Hyden, Western Australia: a low stone wall on top of the outcrop captures rainwater for a dam on the far edge of the granite.

Geographical fact

The explorer Edward John Eyre, when on the dry west coast of South Australia, noted in his diary that he found

> a few drops of water trickling down a huge granite rock abutting on the sea-shore. This was the only approximation to running water which we had found since leaving Streaky Bay, and though it hardly deserved that name, yet it imparted to me as much hope, and almost as much satisfaction, as if I had found a river.

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Sedimentary rocks and landforms

sandstone a rock composed mainly of sand-sized grains (diameter of 0.2–2 mm), most often quartz grains, with the matrix between these grains being made up of clay-sized particles (<0.05 mm in diameter). The rock is welded together by a cement or binder, generally siliceous (silica) or sometimes calcareous (calcite).

limestone a rock made up of calcium carbonate ('lime'), originally deposited under the ocean and formed from broken-up shells, corals, animal skeletons and other carbonate materials

shale a rock composed of mostly clay-sized particles that have been compressed

Sedimentary rocks form from sediments deposited in layers (beds), which have later been compressed into solid rock. Many inselbergs in Australia are composed of granitic rocks, but such upstanding features in otherwise fairly flat areas can form on different rock types. Uluru, for example, is composed of a particular kind of **sandstone**, which is a sedimentary rock. Other sedimentary rocks include **limestone** and **shale**. Because all sedimentary rocks are deposited in layers, it is very easy to see whether the rock has been folded or faulted. If the beds have remained nearly flat-lying, plateaus can form, like those in the Blue Mountains in New South Wales. This area has mainly horizontally bedded sandstone, apart from the Lapstone Monocline on its eastern boundary. Most plateaus have been dissected by streams, but the crests between the valleys will all have approximately the same height, as in the Blue Mountains.

More usually, sedimentary strata have been folded or tilted; in the case of Uluru, beds have been tilted nearly vertically to an angle of 85°. Along the east coast of the Adriatic Sea in the Mediterranean, limestone beds of the Dinaric Mountains have been folded and tilted, and dramatic mountain scenery with deep gorges has resulted from rivers cutting canyons through the mountains in order to reach the sea. Other landforms associated with limestone are also present: disappearing streams, deep solution hollows, sharp-edged rock where fractures are close together and numerous caves.

Contrasting with sandstone and limestone is shale, which is readily weathered and often produces subdued landscapes with gentle slopes and hills. These landforms appear in the Sydney Basin. Where steep slopes develop on shale, dissection has often been rapid and the climate is fairly dry so that weathering and erosion are slowed down.

Source 1.21 Edges of steeply dipping sandstone beds form corrugations on the surface of Uluru, Northern Territory.

Source 1.22 Canyon of the Morača River in the Dinaric Mountains, Montenegro. A road tunnel has been constructed through the cliff on the left.

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ACTIVITY 1.11

1. Using the internet, find images of landforms developed on granite and on sedimentary rocks.
2. Indicate at least 1 landform that occurs only on igneous rocks; 1 that occurs only on sedimentary rocks; and 1 that develops on both igneous and sedimentary rocks.
3. Analyse whether climate seems to be the main control over which landforms develop on igneous and sedimentary rocks.

Metamorphic rocks and landforms

Metamorphic rocks are those that begin as igneous or sedimentary rocks, and have since been subjected to extreme pressure or temperature. For example, granite can be changed into **gneiss** and shale can be transformed into the much harder rock, **slate**. Because of compressive stresses during its formation, slate splits easily along planes to produce smooth leaves or plates, allowing the plates to be used as roofing tiles in older public buildings and residences. In the United States, slate is also advertised as being ideal for billiard tables, as it provides a smooth, tough surface and, properly installed, does not require high maintenance. When limestone is severely compressed, it forms **marble**, a rock that often has attractive colouring due to impurities like iron being present. Marbles in Australia are nearly all coloured, while the Carrara quarries in Italy produce white/grey marble that is exported around the world. Carrara marble has fewer impurities and is therefore more resistant

gneiss originally a granite-type or a sedimentary rock that has been subjected to strong pressure, which also involves high temperatures, resulting in light- and dark-coloured minerals forming bands

slate shale changed into a stronger rock by heat and pressure within the Earth's surface

marble limestone that has been subjected to high pressure and temperature, resulting in recrystallisation of the original calcite crystals into a dense non-banded rock

Source 1.23 The Parthenon, originally constructed more than 2000 years ago on the Acropolis, Athens from Greek marble.

Source 1.24 A Carrara marble statue of Queen Victoria in Perth, Western Australia

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to weathering. This is why coloured marbles are generally used for coffee tables or interior cladding in building foyers, while white marble is used for outdoor statues and monuments. In the Dinaric Mountains in Croatia, the limestone is variable in terms of the extent to which metamorphism has taken place – some areas have been subjected to extreme pressure, while others have not. Damaging earthquakes continue to occur in this region as a result of plate movements, leading to the collapse of hotels and other buildings, and the need to completely reconstruct historic parts of towns like Budva on the coast in Montenegro. Further south, earthquakes have destabilised and damaged the much older Acropolis monuments in Athens, Greece.

Geographical fact

Carrara marble has been used in major monuments and buildings around the world, including Marble Arch, London (1833), Sheikh Zayed Grand Mosque, Abu Dhabi, United Arab Emirates (21st century), Akshardha, the Hindu complex in Delhi, India (opened 2005) and the Peace Monument, Washington, DC (1878).

NOTE THIS DOWN

Copy the graphic organiser below and summarise what you have learned about the 3 main groups of rocks.

Igneous	• Originate from the solidification of magna
Sedimentary	
Metamorphic	

RESEARCH 1.3

Imagine you are a guide working for a tour operator in Australia. Select an iconic Australian landform (for example, Uluru in Australia's Red Centre) and prepare a script to present to visitors. In your script, be sure to include a discussion of the processes that produced the landform and the activities that may have shaped it in the past and are still doing so in the present.

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Case study 1.3

Limestone caves in Australia

Caves can form in almost any thick limestone beds, so are common in all states of Australia. 'Show caves' are those open to tourists.

Caves form in limestone when water circulates along bedding planes or joints in the rock. As rainwater is slightly acid, even without pollution (with a pH of around 5.5), calcium carbonate goes slowly into solution. Circulating water becomes more chemically active when pH is lowered by organic matter or root respiration of plants, when water temperatures are lower and when water flow is turbulent. Caves often have spectacular formations known as **speleothems**. Speleothems take various forms, including dripstone features such as **stalactites** and **stalagmites**.

speleothems cave formations produced by the evaporation of water flowing down or slowly dripping off cave surfaces

stalactites dripstone features that hang from the cave roof

stalagmites dripstone features that build up on the cave floor

1 Using the internet, find the locations of show caves in limestone in 2 states of Australia.
2 Select 2 caves, 1 in your own state and 1 in another state, and research their characteristics, especially in relation to their size, number of levels and the nature of speleothems. You will find a useful starting point at www.cambridge.edu.au/geography8weblinks.
3 Discuss why characteristics and features of limestone caves differ from one cave to another.

Source 1.25 Major show caves and cave systems in limestone in Australia

State	No.	Names of show caves or cave systems
Qld	3	Crystal Caves, Atherton Plateau; Camooweal Caves, Far Western Queensland; Chillagoe Caves, North Queensland
NSW	7	Jenolan Caves, Blue Mountains; Wombeyan Caves, Southern Highlands; Abercrombie caves, Borenore Caves and Wellington Caves, all in central western New South Wales; Yessabah Caves, northern New South Wales; Wee Jasper Caves, southern agricultural area
WA	7	Nullarbor Plain Caves; Ngilgi Cave, Augusta Caves and Margaret River Caves, south-west Western Australia; Stockyard Gully Caves, central agricultural region near Eneabba; Yanchep Caves near Perth; Tunnel Creek in the Kimberley
SA	5	Yourambulla Cave, Flinders Ranges; Kelly Hill Caves, Kangaroo Island; Koonalda Caves, Nullarbor Plain; Naracoorte Caves and Mt Gambier Caves, south-east South Australia
Vic	2	Buchan Caves, Gippsland; Princess Margaret Rose Caves, western Victoria
Tas	4	Mole Creek Caves and Gunns Plains Caves, north-western Tasmania; Newdegate Cave, southern Tasmania; Kutikina Cave, west coast of Tasmania

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FIELDWORK 1.1 ROCKS IN THE LANDSCAPE

Aim

To locate examples of 2 different rock types, either as outcrops in the field or as dimension stone used in buildings or monuments. You will describe the rock and its use, the sites examined and the general location of sites in relation to earthquake and volcanic activity.

Method

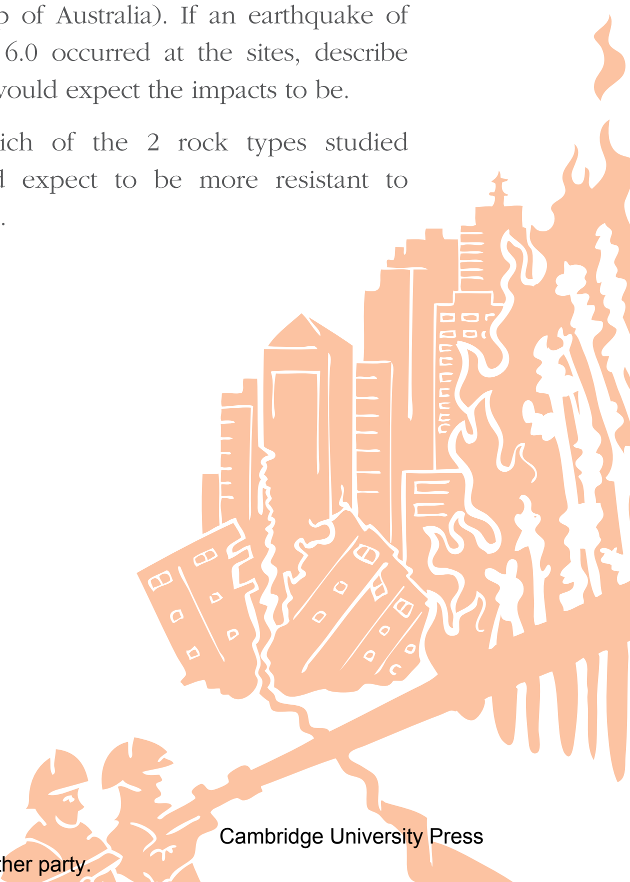
Characteristics of the rocks examined and nature of the sites will be described, and additional information obtained from internet sources.

Preparations

Before going to the field area, prepare a base map with a scale and north sign. If studying outcrops in the field, check with a geology map beforehand to note the field site locations and rock descriptions provided in the map's legend. Take a camera for recording images, a clipboard with your base map, writing paper or a field notebook, and a pen.

Data collection

1. Mark the locations of field sites on your base map and take images of the sites.
2. Describe the field sites of outcrops in terms of local topography, and make notes and sketches of the extent and morphology of the exposures (e.g. large flat area, small boulders). Take note of whether outcrops are few and separated by areas of sediments, or whether they form part of rocky terrain (see item 6). For buildings/monuments, describe the nature of the building and sketch where the studied rocks are situated on the building/monument. Note down any dates that indicate the age of the structure. (When used in buildings and monuments, the rock is freshly cut before use. Dates on building foundation stones and monuments show how long the rock has been exposed to weathering.)
3. Describe the rock types studied using terms like overall colour, the colours of any minerals that can be seen, the size of individual grains within the rocks (clay, silt, sand, gravel or combinations of these) and whether the rock has a uniform, banded or speckled (crystalline) appearance. After you have described them and recorded images, look at hand specimen examples on the internet on a site like www.cambridge.edu.au/geography8weblinks. Are your rock types igneous (intrusive or extrusive), sedimentary or metamorphic?
4. For outcrops, note whether the rock types studied have been used as building stone in the local area or whether you think they would be suitable for that purpose. For buildings/monuments, try to find out where the stone came from (that is, whether it is local stone or quarried somewhere far away). For both kinds of study site, library materials on local history are often useful. Have the rock types studied been used for purposes other than building in the local area?
5. Using the internet and your base map of site locations, find out how far the sites are from any volcanic activity. Is the nearest volcanic activity located on the edge of a continental plate? Are the study sites in a zone of earthquake hazard? (see www.cambridge.edu.au/geography8weblinks for a recent earthquake hazard map of Australia). If an earthquake of magnitude 6.0 occurred at the sites, describe what you would expect the impacts to be.
6. Assess which of the 2 rock types studied you would expect to be more resistant to weathering.



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Fieldwork presentation layout

Front page	Title and name
Contents page	Do this last, as well as numbering pages
Page 1	Aims and methods
Page 2	Location map showing field sites (or building locations)
Pages 3–4	Description of the study sites, with sketches and/or images
Pages 5–6	Description of rock types, with images
Page 7	Uses of studied rock types in local area
Page 8	Description of study sites in relation to volcanic and earthquake activity
Page 9	Evaluation of possible effects of earthquakes on study sites
Page 10	Assessment of the comparative durability of the rock types studied
Page 11	Appendix, bibliography, glossary

Chapter summary

- There are many different types of landscapes, including coastal, riverine, arid, mountain and karst.
- Landforms are naturally formed features on the Earth's surface. Physical geographers attempt to explain the differences in scale, morphologies and groupings of landforms.
- The Earth's crust has broken into about 9 major continental and oceanic plates, which are moving slowly at different rates and in different directions.
- Convergent, divergent, subduction and transform plate boundaries lead to different types of landforms.
- Rocks respond to compression and strain by folding and faulting, and in the process produce distinctive landforms.
- The frequency and timing of volcanic activity is unpredictable but the locations of volcanoes are associated with plate boundaries and hotspots.
- Igneous, sedimentary and metamorphic rocks may produce different or similar landforms, depending on the nature of the rocks, and their weathering and erosional environment and history.

End-of-chapter questions

Multiple choice

1 Sial is:

A an oceanic plate
B a type of volcano
C another name for limestone
D the composition of continents

2 Continental collision boundaries are characterised by:

A a wide continental shelf
B high mountains
C subduction of the slower-moving plate
D the formation of rift valleys

3 Folding occurs:

A in sedimentary rocks
B in igneous rocks
C only in oceanic plates
D below the crust

4 Volcanic activity happens because:

A the Earth is warming
B molten rock in the Earth's core is expanding
C weaknesses in the crust allow molten rock to erupt
D all rocks are produced by volcanoes

5 Some landforms on granite are different from those formed on limestone. This is because:

A granite is more resistant than limestone
B limestone is mainly present on subducted oceanic plates
C granite is made up of durable, compacted shell fragments
D limestone is a weak volcanic rock

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Short answer

1 Identify the difference between 2 kinds of landscapes, listing examples of both.

2 Describe 4 different types of volcanoes.

3 Explain why different landforms develop along divergent and subducted plate boundaries.

4 Discuss how the theory of plate tectonics developed.

5 Suggest why folds and faults develop in rocks.

Extended response

To what extent are landforms developed as a result of plate movements? Discuss this question in a short report by giving examples of both large-scale and small-scale landforms, showing your understanding of the role of plate movements in landform development. What other factors may affect landform formation?

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Source 1.26 Lake Cave, Margaret River, Western Australia

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