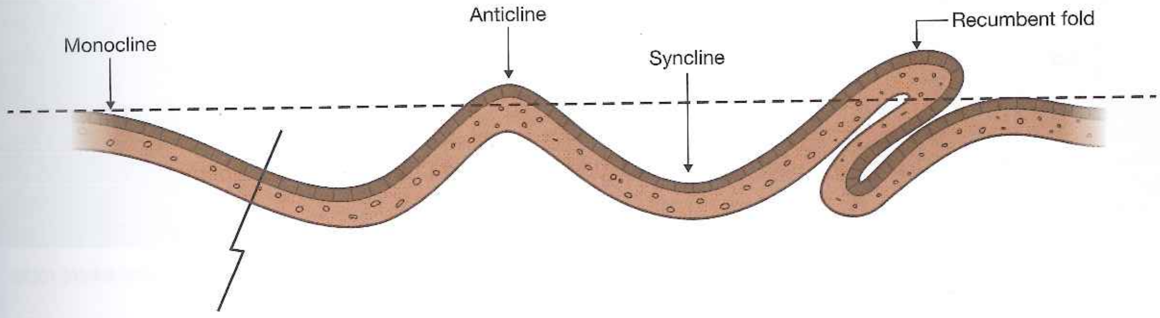
## Rocks responding to pressure

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

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 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.

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





## 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

## 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 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.

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





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

**ephemeral drainage** drainage lines without permanent water flow

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?

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

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'**.

**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.

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

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.

**brackish** containing salt levels between those of fresh water and seawater

## 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.



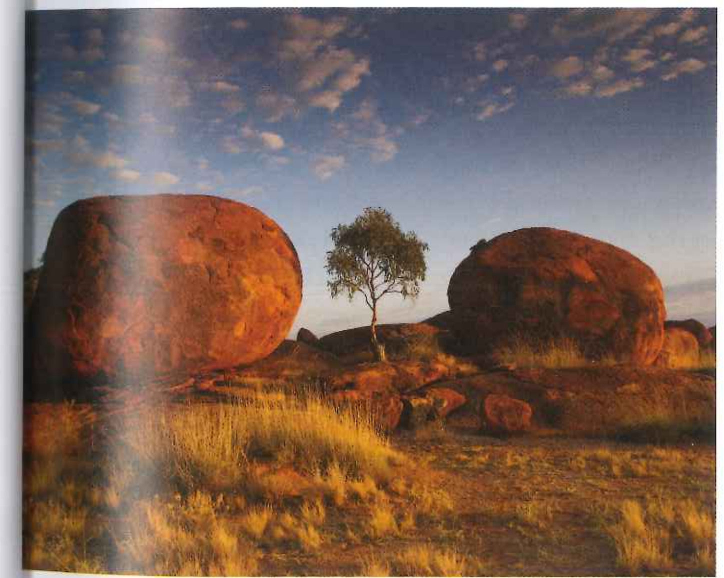


## ACTIVITY 1.8

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