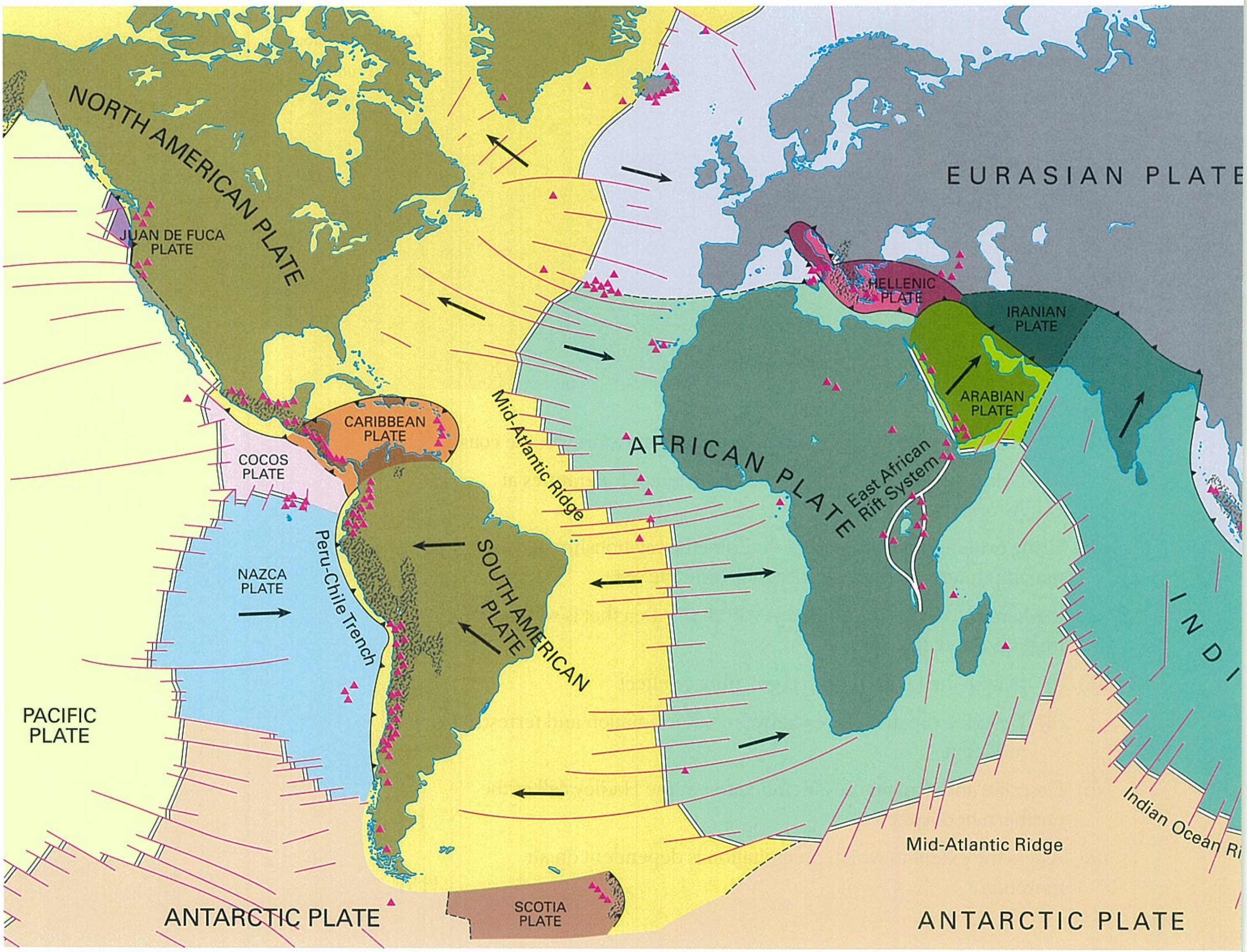
# 3 Rocks and weathering

In this chapter you will learn about:

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




**Figs. 3.1** The world's tectonic plates

# Plate tectonics

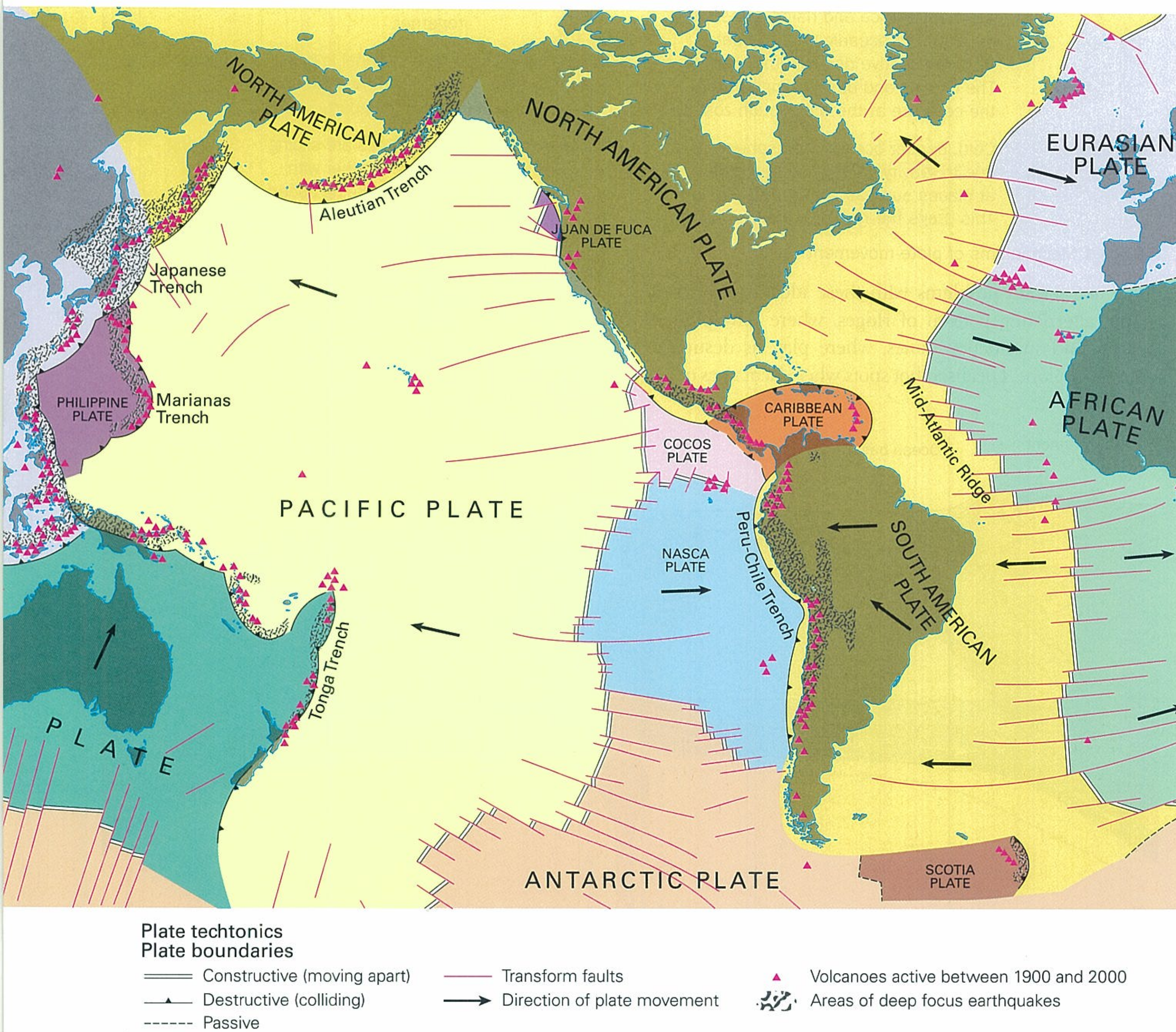
## Global patterns of plates

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

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

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

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



## Plate movements

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

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

**Table 3.1** Mechanisms of plate movement

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

## Plate boundaries (plate margins)

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

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

**Table 3.2** Types of plate margin

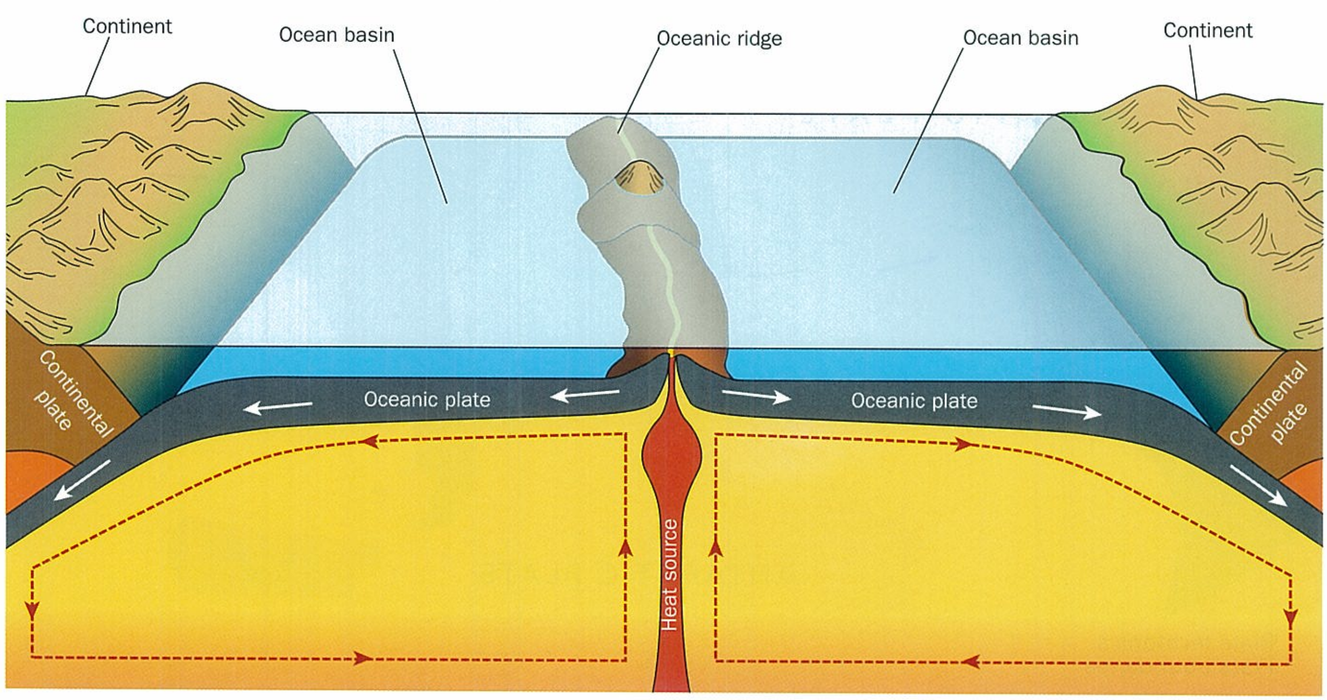



**Fig. 3.2** Mechanisms of plate movement

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

# Convergent plate boundaries

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

## Continental-oceanic convergent plate boundaries

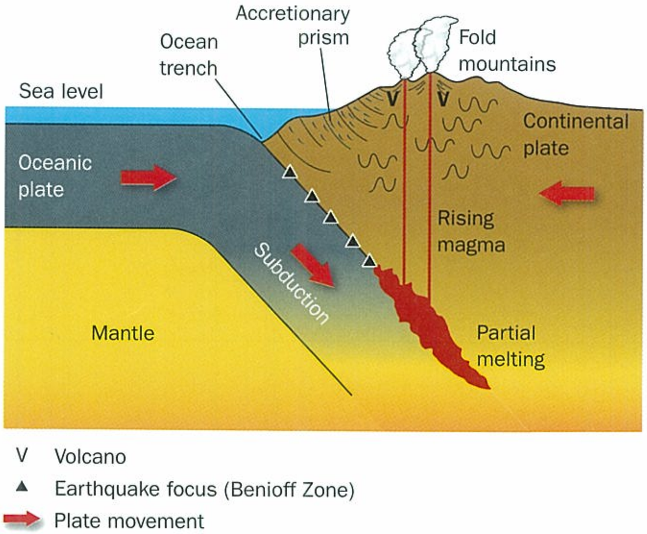



**Fig. 3.3** A cross-section through a continental-oceanic convergent plate boundary

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

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

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

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

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

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

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

## Oceanic-oceanic convergent plate boundaries

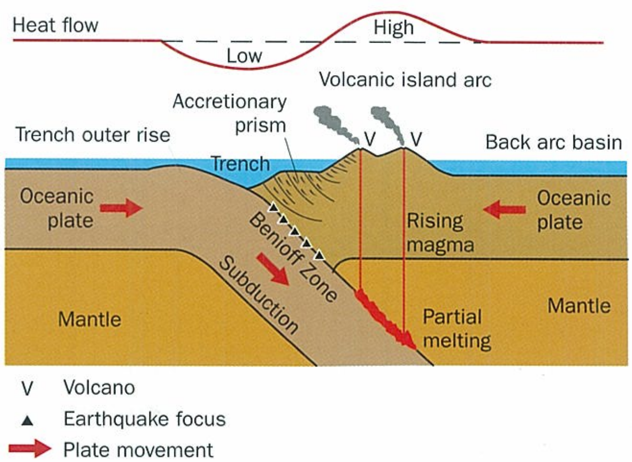



**Fig. 3.4** A cross-section through a oceanic-oceanic convergent plate boundary

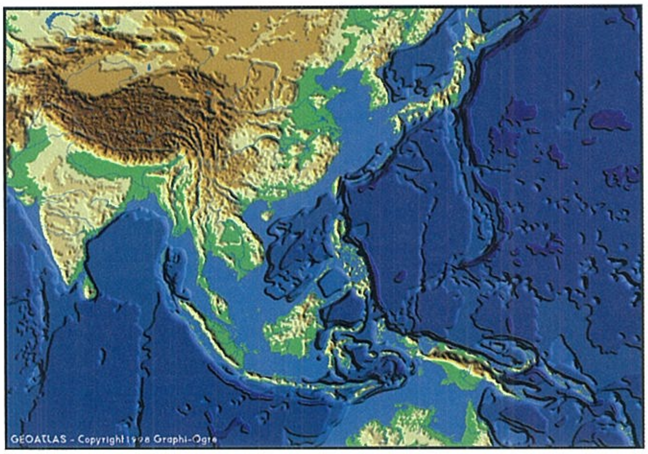



**Fig. 3.5** The south-west Pacific Ocean showing island arcs and ocean trenches

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

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

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

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

## Continental-continental collision boundaries

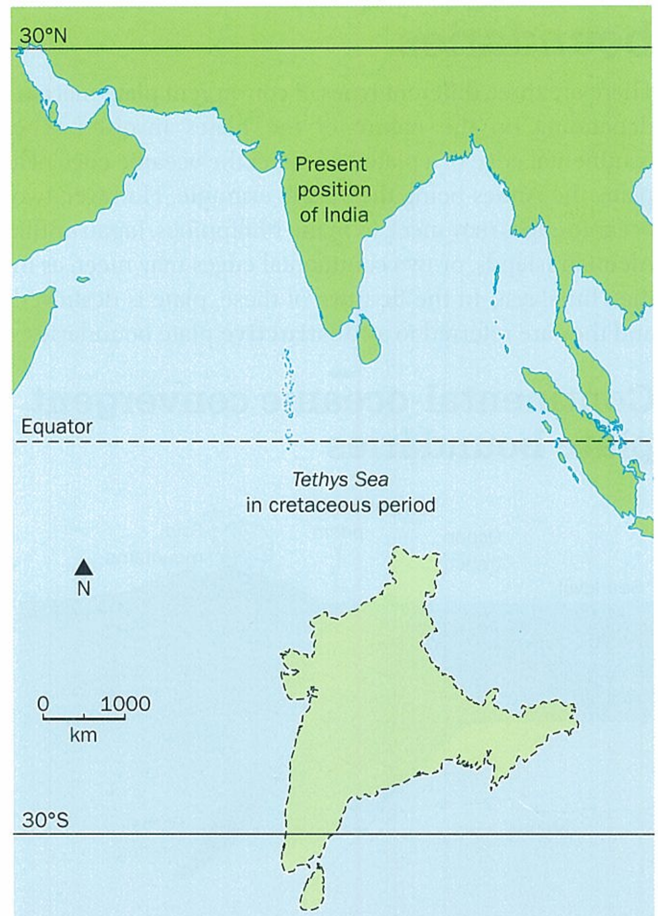



**Fig. 3.7** The northward drift of India and the closure of the Tethys Sea

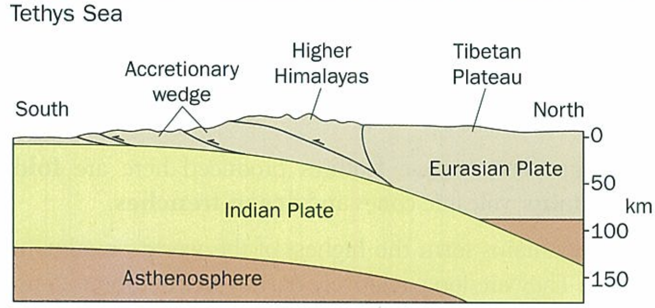



**Fig. 3.8** Indian Plate is being forced beneath the Eurasian Plate. Sediments deposited in the Tethys Sea now form an accretionary wedge of folded sediments which is forced upwards to form the mountains.

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

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

# Divergent plate boundaries

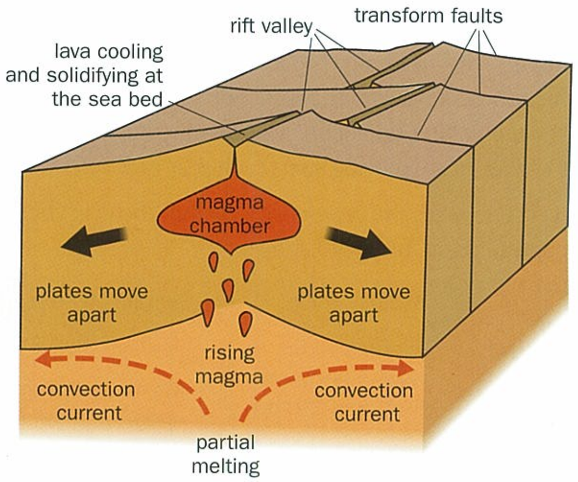



**Fig. 3.9** A block diagram through a divergent plate boundary

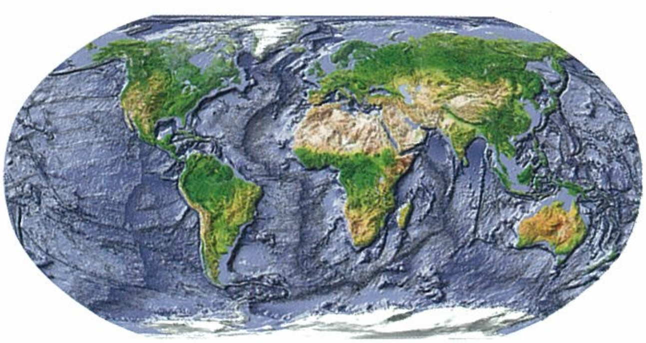


**Fig. 3.10** The deep ocean floor showing the form of ocean ridges

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

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

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

## Continental drift

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

### Coastline fit

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

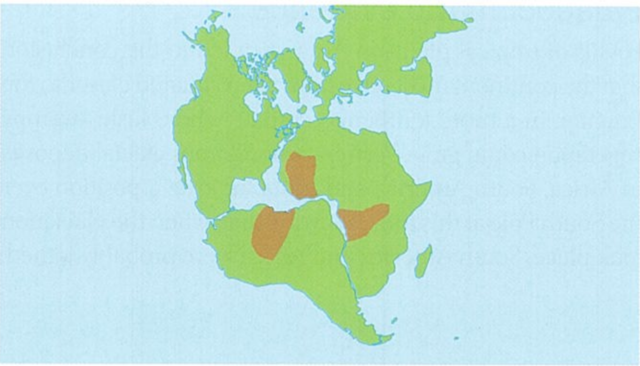


**Fig. 3.11** The fit of the Atlantic continents. The shaded areas show rocks more than 2000 million years old

### Fossils, flora and fauna

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

### Fit of orogenic belts

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

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

### Fit of rock types

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

### Palaeoclimatic evidence

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

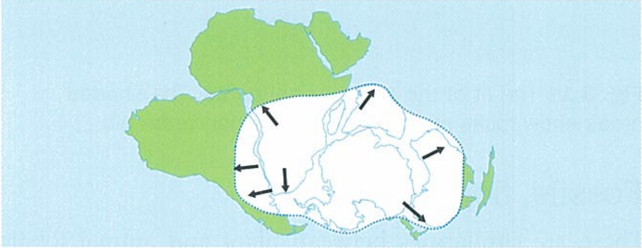


**Fig. 3.13** The position of an ice sheet over the southern continents about 280 million years ago. The arrows show the ice movement directions indicated by features in the glacial deposits

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

## Sea-floor spreading

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

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

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

**Table 3.3** A comparison of the oceanic and continental crust

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

### Evidence for sea-floor spreading

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

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

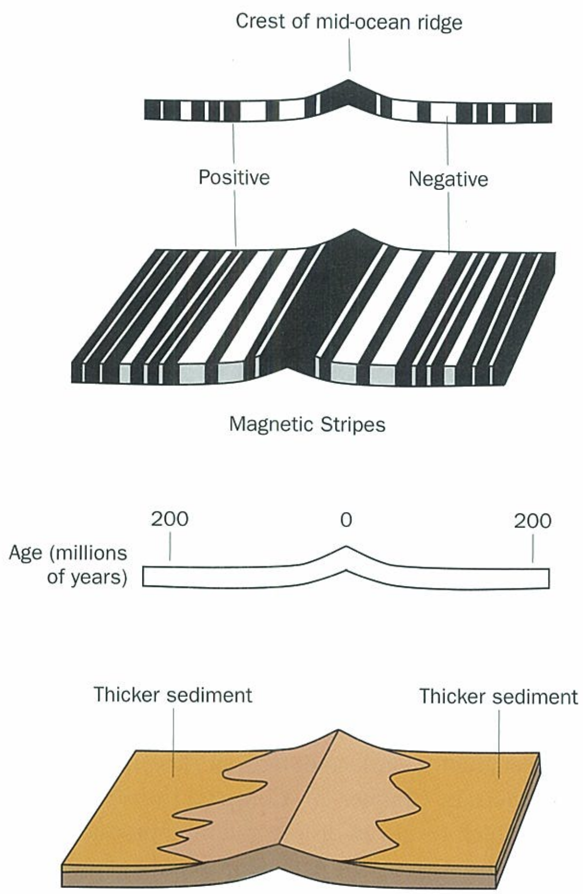



**Fig. 3.14** Magnetic stripes, ocean floor sediments and the age of the ocean floor

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

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

## Hot spots

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

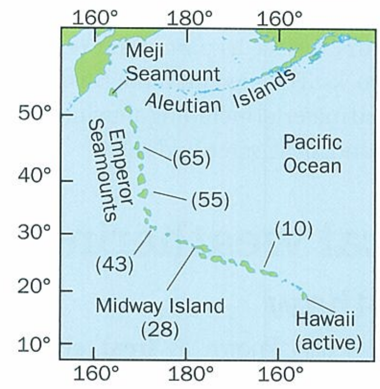



**Fig. 3.15** The Hawaiian volcanic islands and the Emperor seamounts. The number in brackets is the age of the islands in millions of years

**8.** Using Fig. 3.15, describe the direction of plate movement

(a) between today and 43 million years ago

(b) between 43 and 65 million years ago.

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

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

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