3 Rocks and weathering

3.1 Plate tectonics

The Earth's interior

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

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

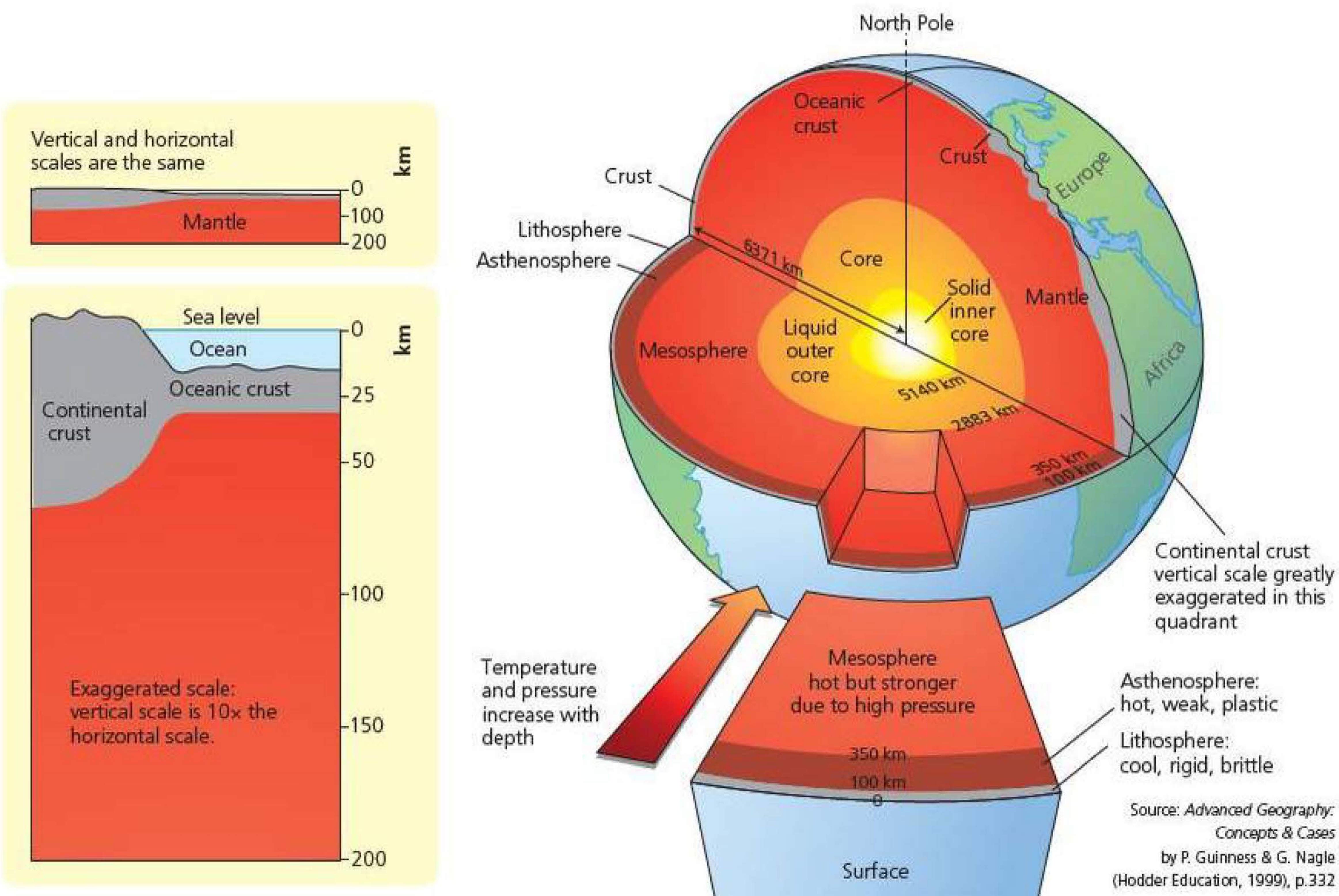


Figure 3.1 The Earth's internal structure

Table 3.1 A comparison of oceanic crust and continental crust

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

The evidence for plate tectonics and their global patterns

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

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

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

The evidence of plate tectonics includes:

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

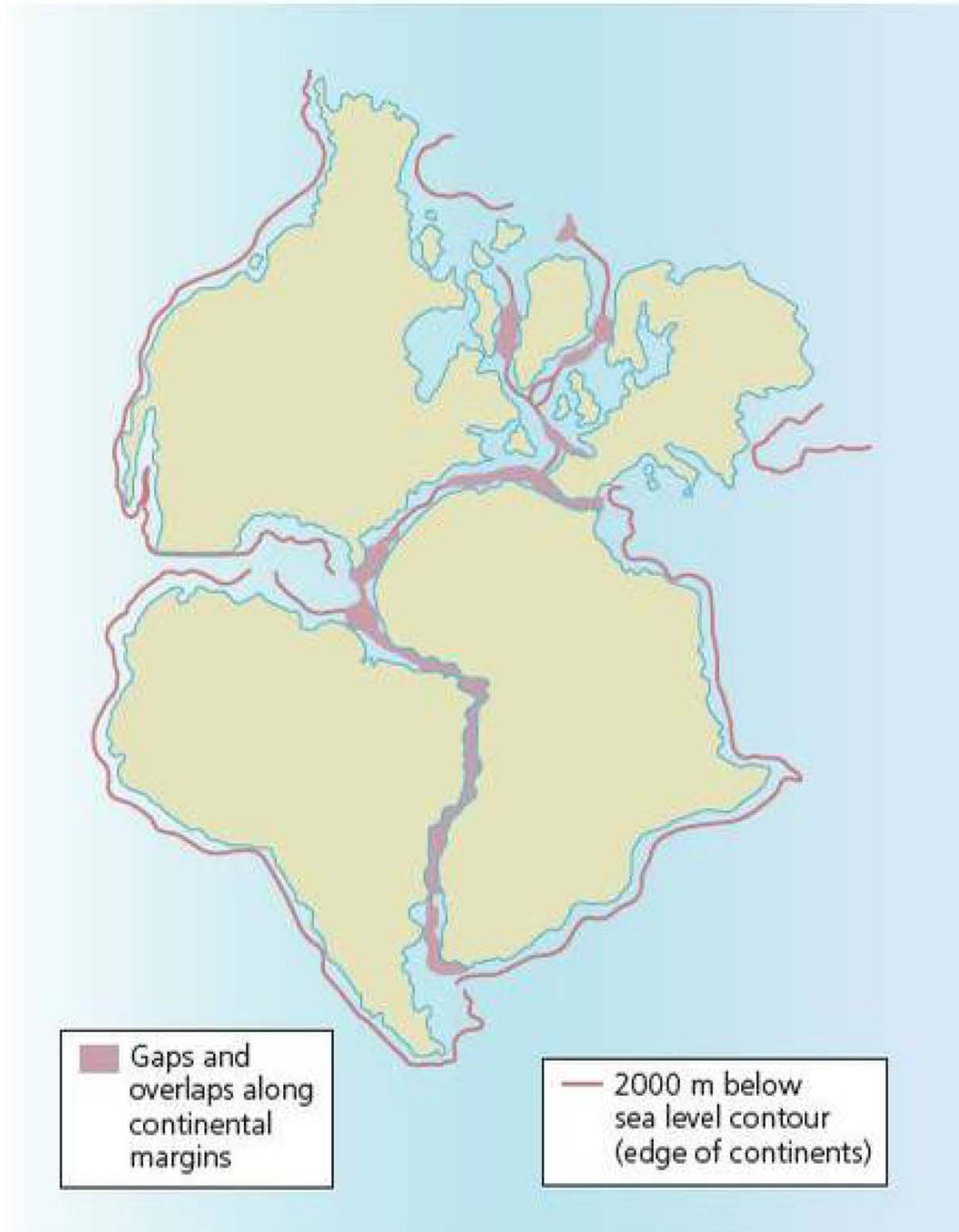
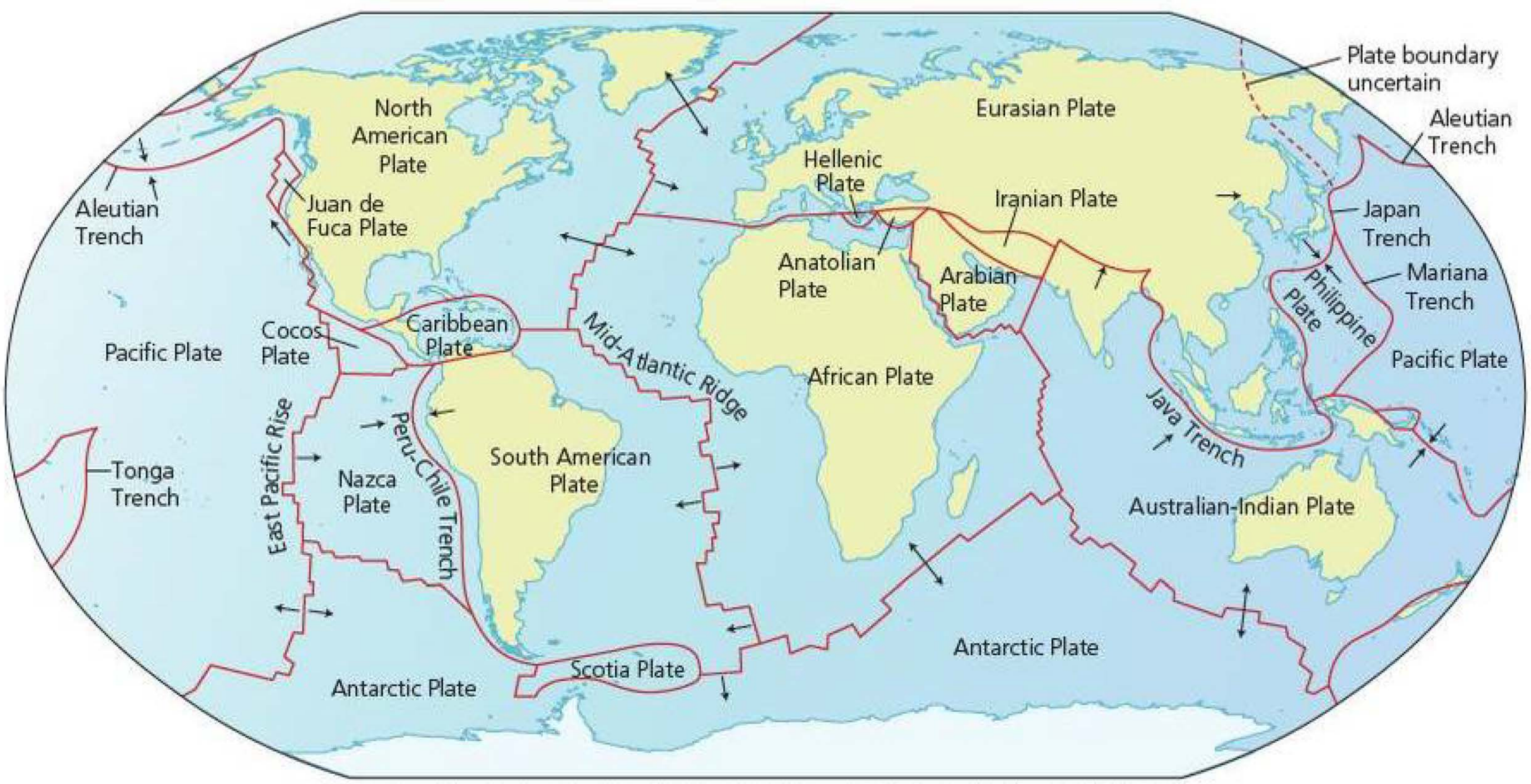


Figure 3.2 Evidence for plate tectonics

Plate boundaries

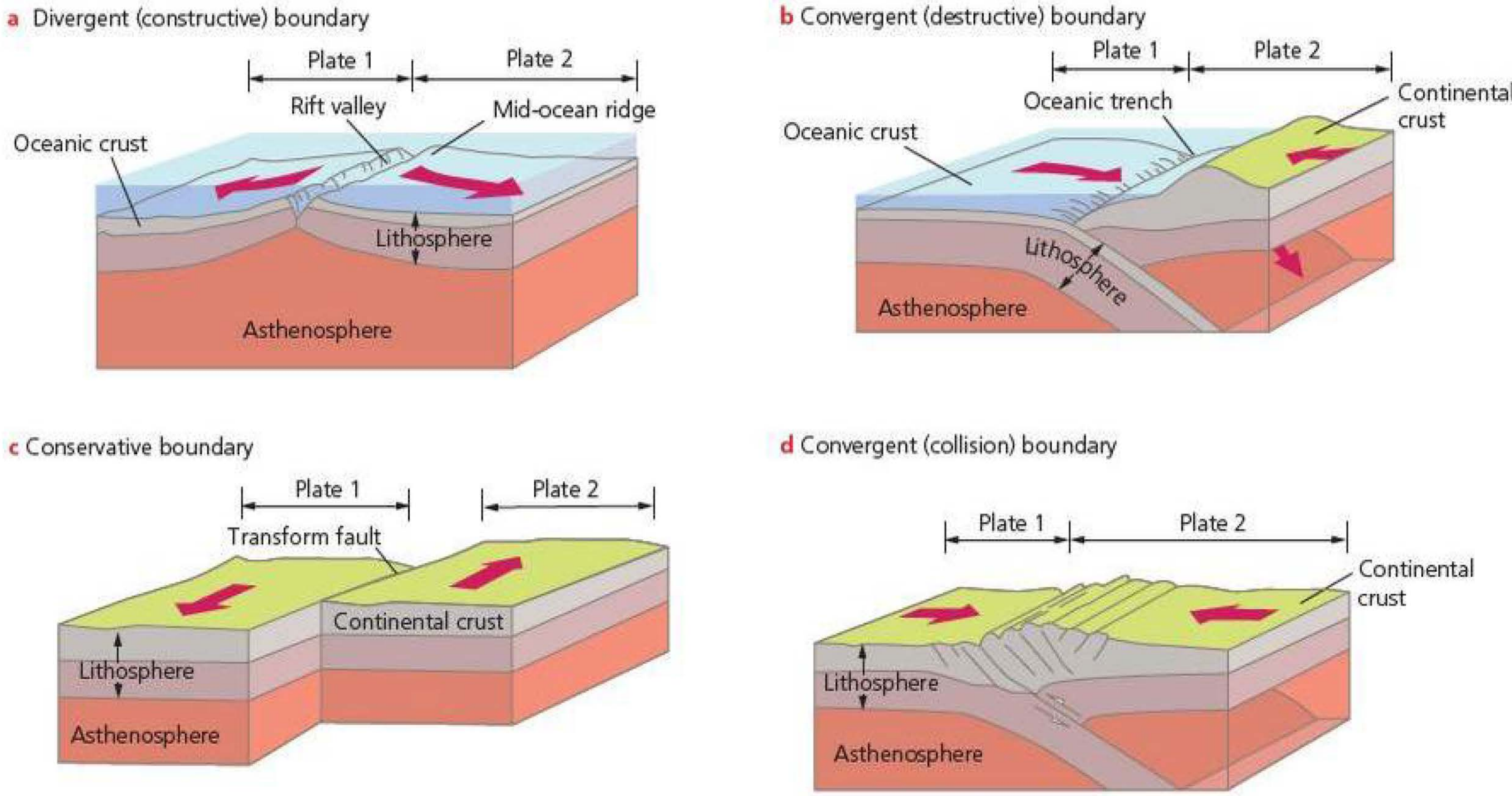
The zone of earthquakes around the world has helped to define six major plates and a number of minor plates (Figures 3.3 and 3.4). The boundaries between plates can be divided into three main types: divergent (constructive) boundaries, convergent plate boundaries (including destructive and collision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

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



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

Figure 3.4 Plate boundaries



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

Figure 3.5 Types of plate boundary

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

The movement of plates

There are three main theories about movement:

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

Section 3.1 Activities

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

Processes and associated landforms

Sea-floor spreading

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

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

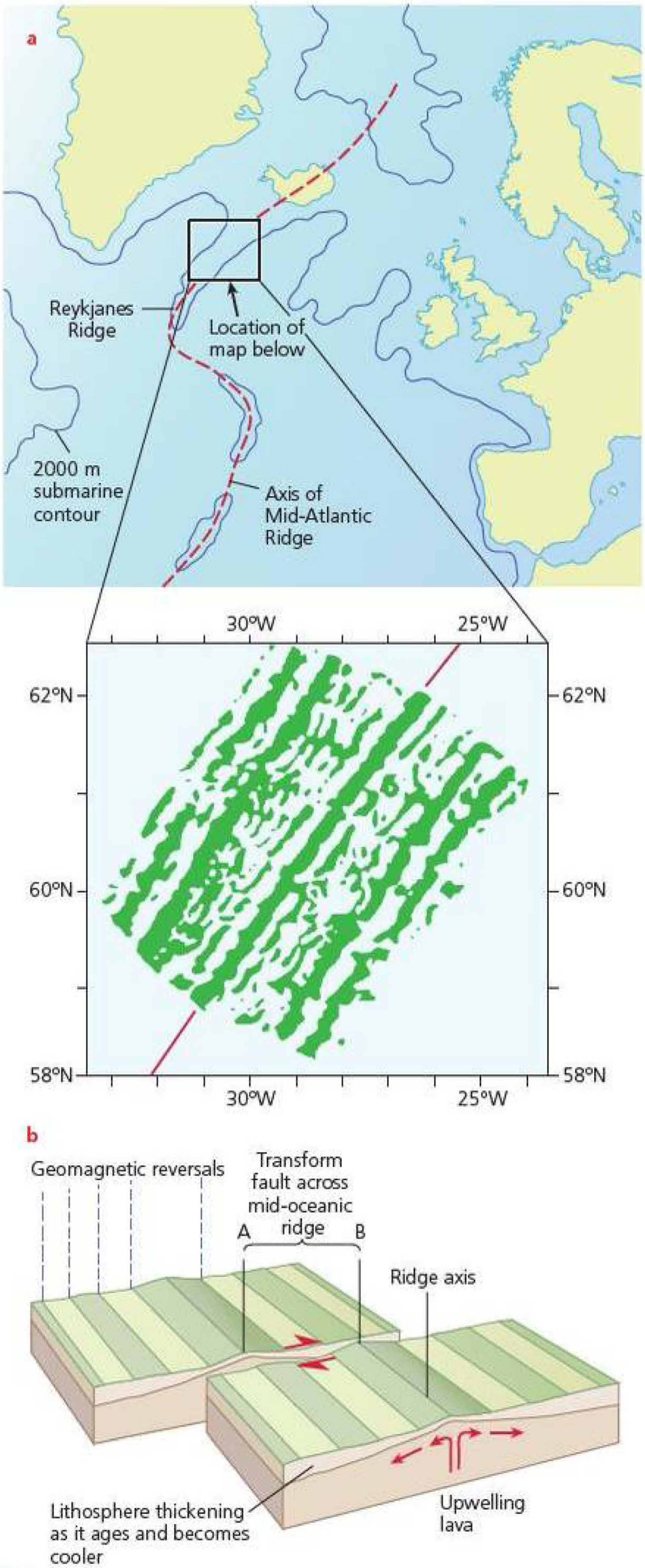


Figure 3.6 Sea-floor spreading and paleomagnetism

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

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

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

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

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

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

Section 3.1 Activities

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

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

Subduction zones and ocean trenches

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

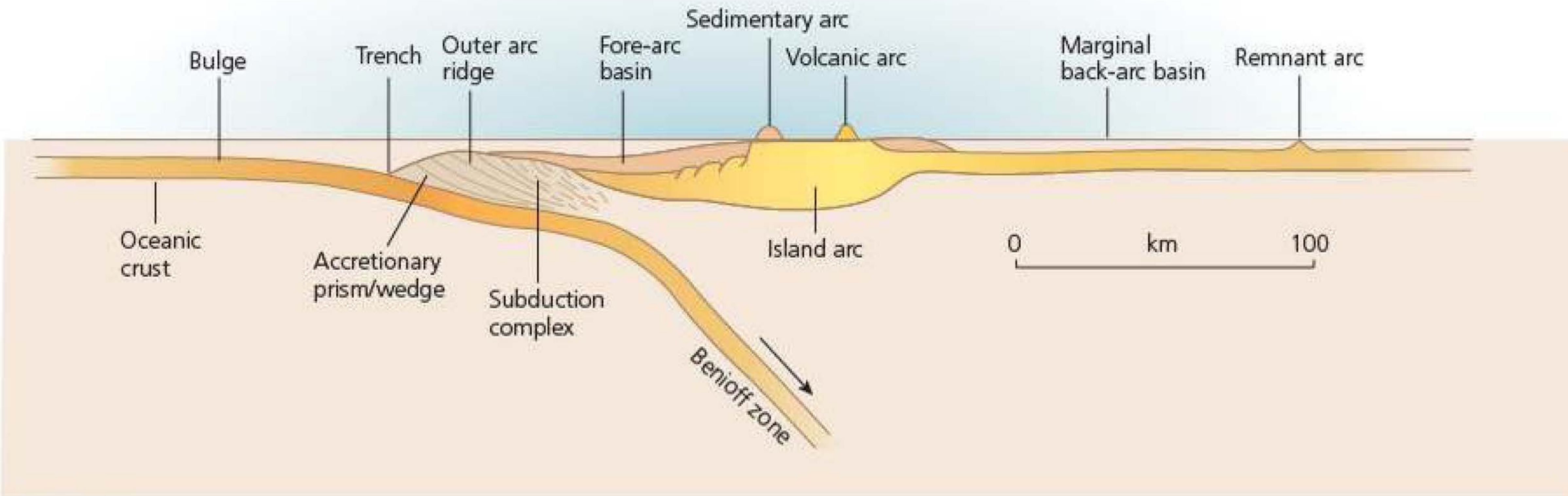


Figure 3.7 Ocean–ocean subduction zone

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

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

The evidence for subduction is varied:

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

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

Benioff zone

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

Section 3.1 Activities

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

Fold-mountain building

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

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

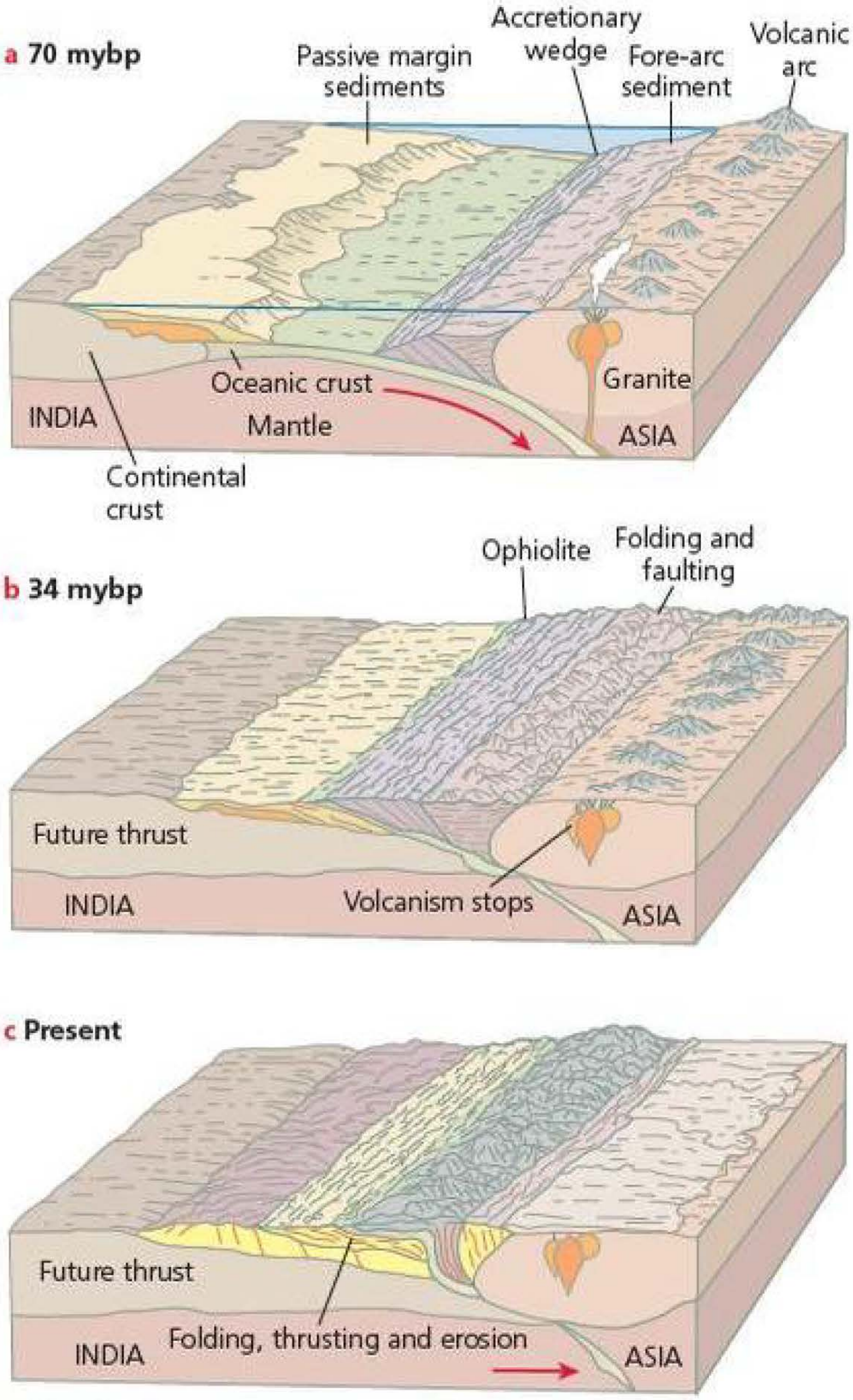


Figure 3.8 Formation of the Himalayas

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

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

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

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

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

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

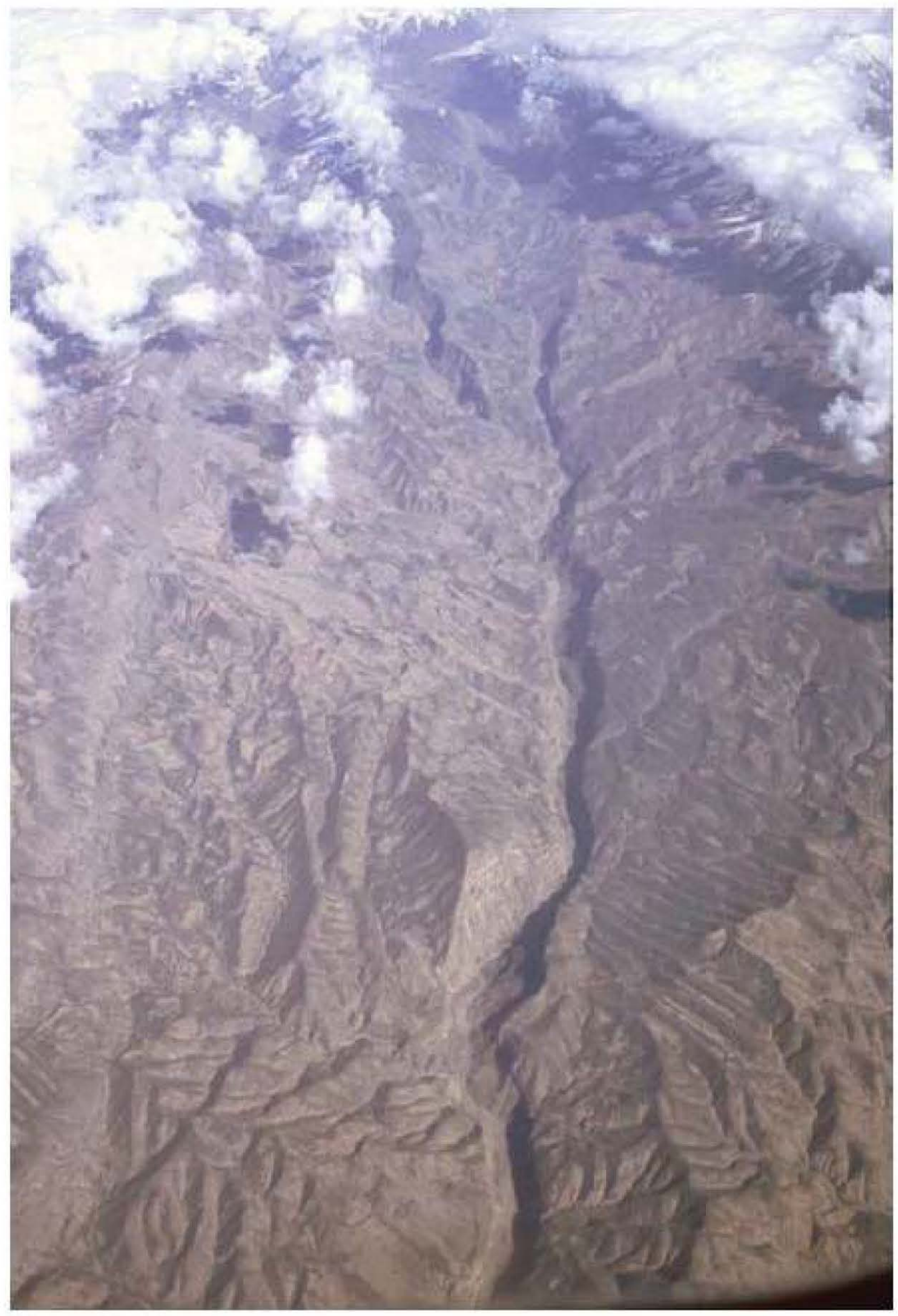


Figure 3.9 Fold mountains

Section 3.1 Activities

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

Ocean ridges

The longest linear, uplifted features of the Earth's surface are to be found in the oceans. They are giant submarine mountain chains with a total length of more than 60 000 kilometres, between 1000 and 4000 kilometres wide and have crests that rise 2 to 3 kilometres above the surrounding ocean basins, which are 5 kilometres deep. The average depth of water over their crests is thus about 2500 metres. These features are the mid-ocean ridges, famous now not only for their spectacular topography, but because it was with them, in the early 1960s, that the theory of ocean-floor spreading, the precursor of plate tectonic theory, began. We now know that it is at these mid-ocean ridges that new lithosphere is created.

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

Volcanic island arcs

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

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

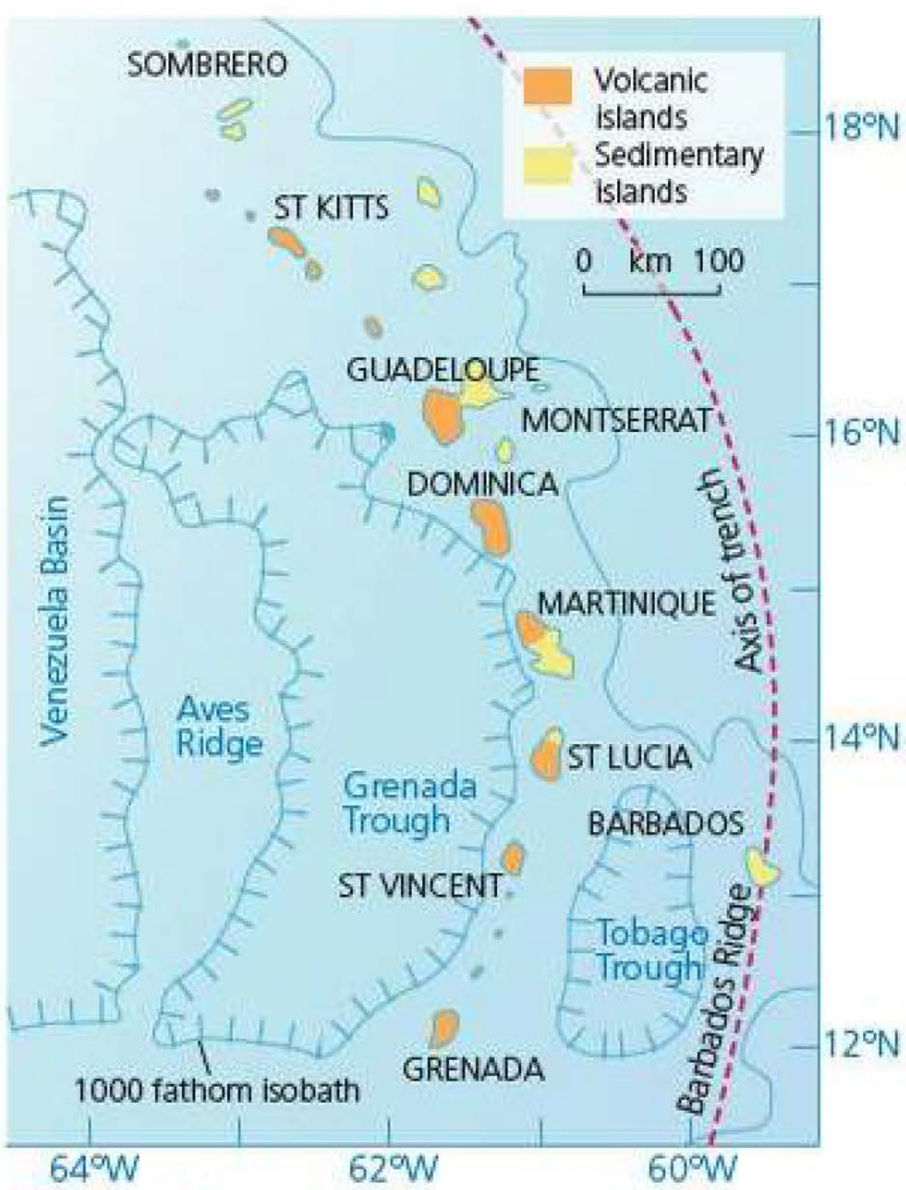


Figure 3.10 Island arcs in the Caribbean