World Geomorphology

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Chapter

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Continental drift and plate tectonics

Science fiction is a literary form which enables authors to imagine amazing and sometimes frightening ideas of what life may be like on other planets or even on earth at some time in the past or future. Sometimes fact is stranger than fiction for one of the most intriguing stories of scientific discovery concerns our own planet, Earth, and the way the continental areas have evolved and assumed their present distribution.

For a long period geographers and geologists thought that there was a strong degree of permanence in the distribution and form of the continents and ocean basins. Although the highest mountain on land and the deepest parts of the sea were of great interest, it was significant that the average level of land occurs at 870 m above present sea level and that the average depth of the sea is 3800 m below sea level. This average picture, shown on the hypsometric diagram (Figure 2.1), also gives a good idea of the general shape of the ocean basins and their resemblance to a soup dish. The ocean waters slightly overfill the dish and extend on to the gentle slope of the rim. This gentle slope, known as the continental shelf, is bounded on the ocean side by a relatively sharp descent to the ocean depths of the abyssal plain. The North Sea and the shallow seas around Great Britain are a good example of the continental shelf at the present time. However, epicontinental seas such as this have varied considerably throughout geological time and many of the familiar sedimentary strata were laid down in them.

Besides the clear difference in relief, it has been appreciated for the last 50 years that the major landmasses were predominantly composed of lighter mater-

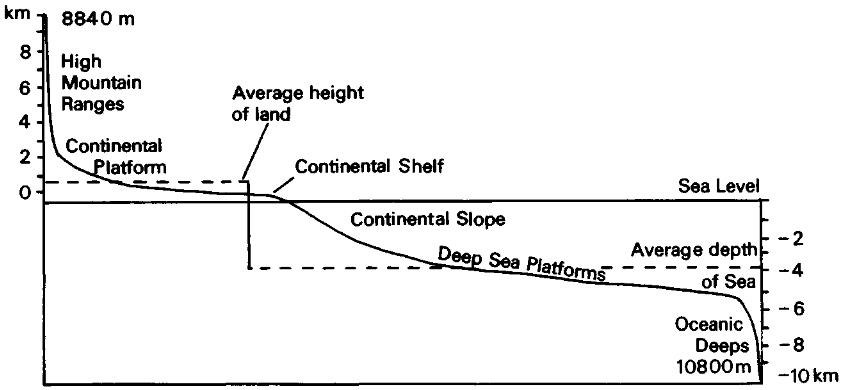

Figure 2.1. The extent of global relief lying at different elevations is shown by the hypsographic curve. The mean continental level is 370 m and the mean oceanic level is −3730 m.

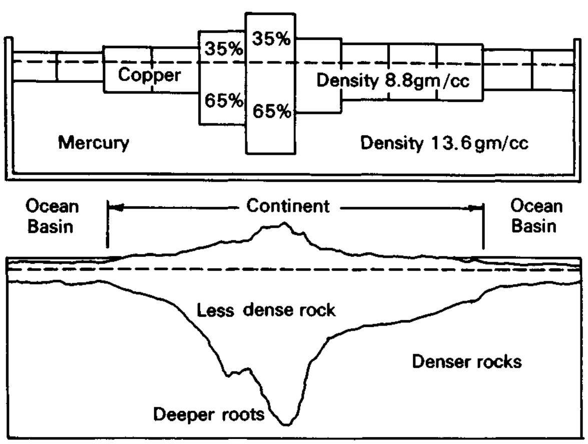

Figure 2.2. The principle of isostasy states that the Earth's crust is in a state of buoyant equilibrium. Blocks of the same density but different lengths will float at different levels; in the case of the Earth's crust the lighter sial 'floats' above the denser sima, but high mountains must be compensated for by deep roots.

ials such as granites, rich in silica and aluminium. Continental material, therefore, received the acronym 'sial', and as it had an average specific gravity of only 2.7 it was thought to 'float' on the denser material which made up the sea floor and which underlies the continental material at depth. The ocean floor material, rich in silica and magnesium became known as 'sima' and had a specific gravity of between 2.9 and 3.0. The discontinuity between granitic and basaltic material has already been mentioned in the previous chapter as lying between 20 and 25 km beneath the surface and is also known as the Conrad discontinuity.

In order to meet the physical requirements imposed by gravity, and for high mountains and deep sea basins to exist, the concept of 'isostasy' was introduced by the American geologist Dutton in 1889. If blocks of wood of different length are floated upright in water, or if blocks of copper are similarly floated in mercury, they assume different elevations in proportion to their length. They also protrude by different amounts into the supporting liquid (Figure 2.2). If this concept is applied to sial and sima, it becomes immediately apparent that the higher the mountain mass, the deeper roots it must have penetrating down into the earth.

Evidence for deep roots beneath large mountain masses was first noted by the French in a scientific expedition to the Andes in the first half of the eighteenth century. A smaller than expected deflection of the plumb-line was observed in the Indo-Gangetic plain in response to the considerable mountain mass of the Himalayas. Once adjustments have been made for elevation and for the effects of the pull of the Sun and Moon, the values of gravity should approximate to calculated values for the idealised ellipsoid Earth. That they do not is further indication that material of lower specific gravity penetrates deeply below major mountain ranges. Evidence from earthquakes suggests that the roots of mountains extend to depths of 40 km or more.

Before the ideas of continental drift were put forward by Wegener in his paper of 1912 and his book of 1915 *The origin of continents and oceans*, geologists were in a great dilemma. It was apparent that there had been considerable crustal shortening as could be seen where the rocks were folded and overthrust. This led them to the conclusion that the Earth had contracted and that the mountains represented the wrinkled crust of the shrinking sphere. A further difficulty was that the climatic conditions in which rock strata had been laid down had varied greatly with the passage of time; either the climate had changed greatly or the continent might have had a different disposition from that of the present day, but how could a continent move?

One ingenious, but unsupportable, scheme was that of Lothian Green. Shrinkage of the globe, he suggested, would lead to a tetrahedral shape with the oceans occupying the faces of the tetrahedron and the continents the edges. Although imaginative, this idea cannot stand up to several arguments; it would be gravitationally unstable and isostatic readjustments would take place causing the corners to sink back into the Earth, and, as can be seen from space, the major relief features of the Earth at true scale scarcely diverge from the circumference of the globe.

The absence of continental material, sial, from large areas of the Earth's surface gave rise to some other interesting theories. One of the most intriguing was that proposed by George Darwin, son of the famous natural scientist Charles Darwin. He suggested that the sialic rocks, missing from the whole of the Pacific basin, had been removed from the Earth and now formed the moon. The Pacific basin was the scar left behind when the Moon was separated from the Earth. Darwin calculated that the combined effects of the rotation of the Earth and the Sun's attraction would produce a tidal resonance which would increase until a mass separated from the Earth. The attraction of this idea was that the Moon has been found to be moving further away from the Earth with the passage of time. However, the tidal resonance theory of the origin of the moon and the resultant lack of sial on the areas of the Pacific Ocean floor was disproved because internal friction would prevent the tidal resonance proposed by Darwin.

Alternative theories now suggest that the Moon is most probably a captured body and that this capture must have taken place simultaneously with the formation of the Earth. Darwin's idea that the removal of material from the Pacific resulted in the movement of the other continental masses to give the ring of mountains and volcanoes which surround the Pacific must also be abandoned, and some other explanation sought for the so-called ring of fire.

Evidence for continental movement has been accumulating since the beginning of the seventeenth century when Sir Francis Bacon noted the complementary nature of the coasts of Africa and South America. A Frenchman in the seventeenth century concluded that America was separated from the Old World at the time of the biblical Flood; other scientists denied the whole affair and suggested that the Atlantic resulted from the foundering of the mythological Continent of Atlantis. Many geological events were seen to have taken place in a catastrophic manner in the early period of geological studies. The correspondence of geological features on both sides of the Atlantic, including the distribution of similar fossil plants in the coal measures of Europe and North America, was first described in detail in 1858.

Continental drift

By the first decade of the twentieth century sufficient information had been accumulated for more definite theories on the movement of continents to be put forward. Two Americans were first in the field: F.B. Taylor (1908) and J.B. Baker (1911) used the idea of continental drift to explain the origin of mountains and the correspondence of relief on either side of the Atlantic. However, the most famous protagonist during this period was undoubtedly Alfred Wegener, who was not a geologist but a meteorologist. Wegener had adopted the idea of continental drift to account for the different climates which had affected continents in earlier geological times. He had amassed a wealth of biological, palaeontological, palaeoclimatic, tectonic and geophysical evidence for the existence of continental drift. Unfortunately, the concept was too much for his contemporaries, who picked holes in his arguments and rejected the hypothesis. In spite of some excellent positive evidence, his proposals really foundered on disbelief, as nobody at that time could envisage a force or mechanism which could move a continent across the face of the Earth.

The evidence collected by Wegener suggested to him that the present distribution of the continents is derived from the disruption of a super continent which he called 'Pangea' (all lands) which had existed in the late Carboniferous (Figure 2.3). The break-up of this large landmass took place in the Mesozoic, with the core areas of the future continents moving towards their present positions. Although Wegener and some of the early workers were trying to show how different climate might have affected the five continents, their maps did

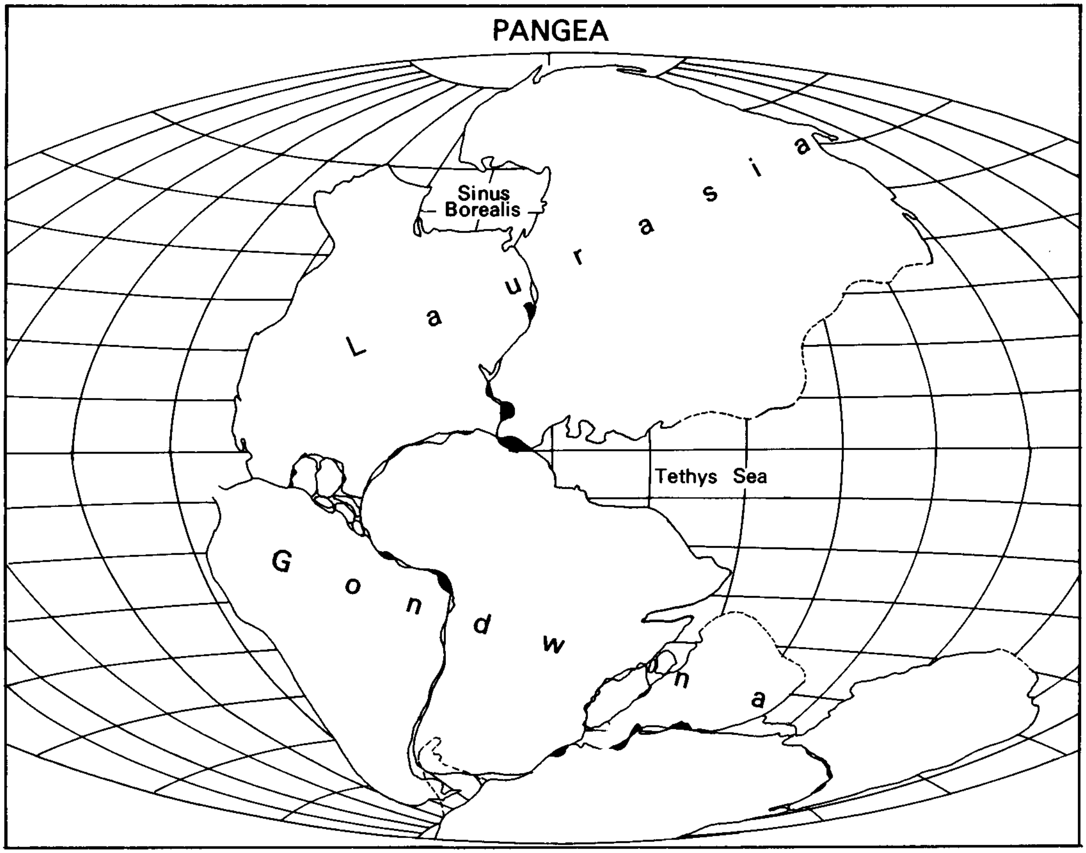

Figure 2.3. A best-fit reconstruction of the continents to form 'Pangea' (all-lands) as it may have been in Permian times. Laurasia and Gondwana were separated subsequently by rifting and movement of the tectonic plates.

not show Europe and North America sufficiently near the equator to have tropical forests. Wegener was well aware of the northward movement of Africa and India as he invoked a force called 'polflucht' to account for their motion. Such a force does in fact exist, but it would have to be many million times more powerful before it could move a continent. Additionally, such a force would not be adequate to account for the generally westward movement of North and South America, and certainly could not explain any reversals of movement which are thought to have occurred.

Other proponents of the continental drift theory, such as du Toit, distinguish between a northern group of continental nuclei, which they called 'Laurasia' and a southern group called 'Gondwana' (Figure 2.4). The name Laurasia is formed from elements of words describing part of North America and Asia. The name Gondwana is taken from a place in India, Gondwana, where fossil plants of the *Glossopteris* flora were first described, only to be found later in South America, Africa, Australia and Antartica. Between Laurasia and Gondwana a geosynclinal area developed beneath a sea known as Tethys. Into this subsiding zone the deposits were laid which eventually became the fold mountains of the Alps and the Himalayas.

Although opinion generally swung away from the idea of continental drift as a practical explanation of continental distribution, the idea was kept alive by one or two active proponents. In South Africa, Alexander du Toit remained convinced of the possibility of continental drift and wrote articles and a book supporting the theory. In Britain, Anthony Holmes can be credited with being the first to suggest a possible mechanism for moving continents. After working on methods of dating

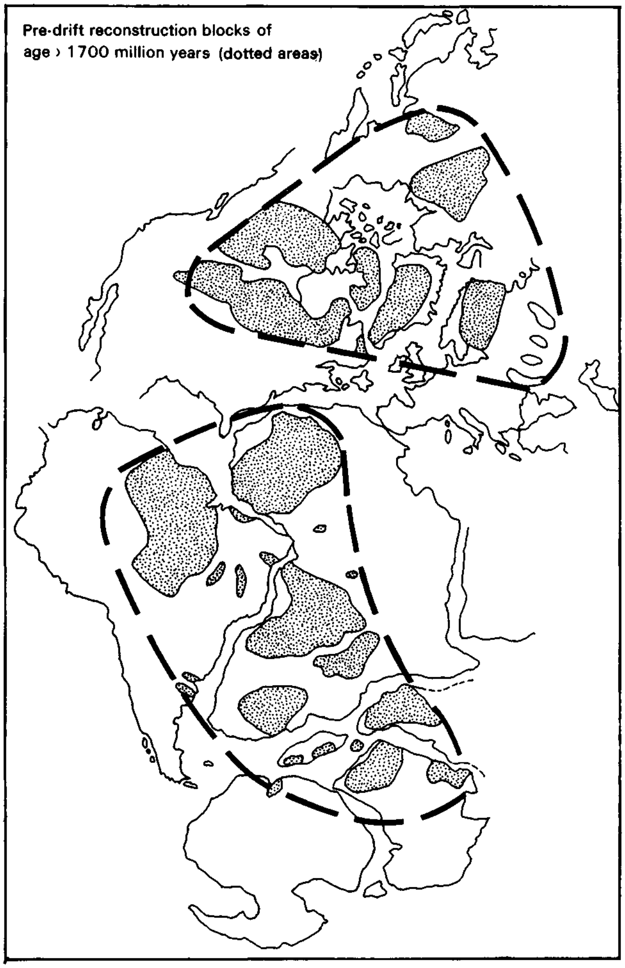

Figure 2.4. Continental nucleii – cratons of 1700 million years ago reassembled into their positions before disruption of Pangea. (After Hurley and Rand, 1969, *Science* 164, 1229.)

Figure 2.5. Simplified plots of continental movement shown by changes in the direction of magnetic north.

rocks by measuring radioactive decay, he proposed that the heat liberated by radioactive disintegration of mineral deep in the Earth's crust would cause convection currents which might raft the continents along.

In spite of the convincing nature of the evidence collected by those scientists who favoured continental drift, the geological establishment of the time was very reluctant to accept the concept of moving continents. Mysterious land bridges were conjured out of nowhere to account for the movement of plants and animals from one continent to another. In the majority of cases, no trace has ever been found of sunken land which could in any way have fulfilled such a purpose. Thus, despite some very good circumstantial evidence, the concept of continental drift went out of favour and remained so until the late 1960s when it was once again revived. A decade later there was virtually complete agreement that continents had moved and that the findings of Wegener concerning the climatic, biological, geological and physiographical characteristics were correct.The convictions and faith of a few scientists, mainly in the southern hemisphere, were finally vindicated in the new approach which came to be called 'plate tectonics'. The evidence which made this new approach possible is considered in the next section.

Plate tectonics

The possibility of continental mobility received fresh impetus from a number of important discoveries made during the two decades, 1956 to 1976. Significantly, these discoveries were made by the very group of scientists (geophysicists) who formerly had doubted the theory of continental drift. Realisation of the significance of residual rock magnetism and the implications of mid-oceanic ridges did not appear separately to have immediate importance for continental mobility. When taken together, however, these concepts provided the opportunity for a complete reappraisal of the ideas of continental drift and for the first time gave a credible means of demonstrating continental motion.

Firstly, a paper published by a group of British scientists in 1956 revealed that the direction of magnetisation of rocks could be related to the position of the

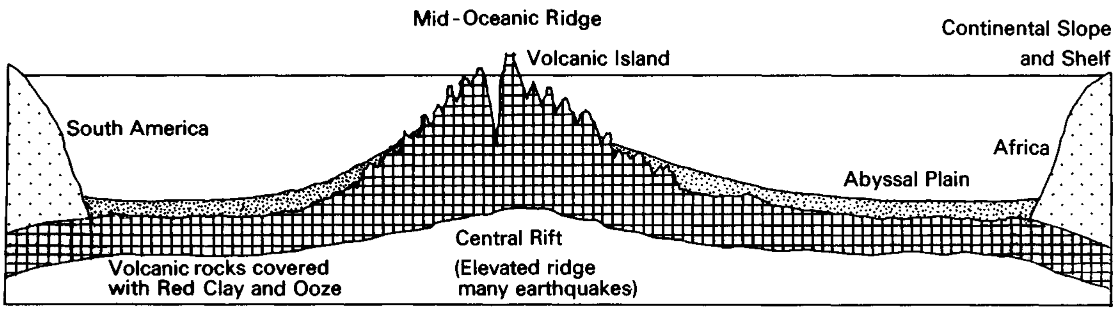

Figure 2.6. Diagrammatic cross-section of the Atlantic Ocean indicating the mid-oceanic ridge.

magnetic pole of the Earth at the time the rocks were laid down. When rocks cool from a magma, and even when sedimentary rocks are deposited, the iron minerals within them become slightly magnetised and their polarity is in sympathy with the Earth's magnetic field at the time and place of formation. By careful measurement it is possible to reconstruct the position of the magnetic pole at different stages of the past history of the Earth. When this was done, it was found that the results were consistent for any one continent, indicating that either the pole or the continent, or both, could have moved. However, when the previous positions of the magnetic pole were plotted for other continents, differences became apparent which can only be explained by a differential movement of the landmasses (Figure 2.5).

A second important hypothesis was proposed by an American, H.H. Hess in 1960, following the realisation that the mid-oceanic ridges were a characteristic feature of not only the Atlantic, but the other oceans as well. It was appreciated for the first time, that the largest and longest mountain range of the Earth's surface lay at the bottom of the sea (Figure 2.6). It possesses peaks which rise from the ocean depths to more than 4000 m above sea level, making a total height greater than Everest, and its length is more than 64 000 km. As this enormous feature of the oceanic floor is composed entirely of volcanic outpourings, Hess suggested that the sea floor cracked open along the line of the mid-oceanic ridge and that new volcanic material came to the surface and gradually spread on either side of the spreading centre. This proposal was attractive as it offered a means of solving the apparent youthfulness of the ocean floors, virtually all of which are post-Cretaceous in age, and explained at the same time why there was a lack of sediment covering much of the sea floor.

Thirdly, during the period 1965 to 1975 there was the realisation that the magnetism in the rocks on the sea floor could be related to the age of the lava and that together these three discoveries could be used to give the most convincing proof yet available that the continental plates had moved and are still moving. As Figure 2.7 shows, the reversals in the Earth's magnetic field are faithfully recorded in the bands of lava extruded from the spreading centre. Each side is pushed further and further apart by the continuing process of lava extrusion at a rate of between 1 and 9 mm per year. The original continental drift theory assumed that the lighter granitic or sialic rocks were floating upon the sima or denser basaltic rocks of the sea floor. The modern interpretation is that the continents are firmly embedded in the sea-floor material which is as rigid and brittle as the continental material. Both continental and sea-floor materials are being moved along together on a large fragment of the Earth's crust which is referred to as a lithospheric plate. Each of these plates is between 150 and 200 km thick and is bounded by a margin which is marked by localised seismic, volcanic and tectonic activity (Figures 2.8 and 2.9). If new material is constantly being introduced along the line of the mid-oceanic ridges and spreading out from them, it follows that it will meet material from another spreading centre. It will either come into direct collison with it, it will override it, or it will itself be overridden (Figure 2.10).

Three types of plate boundary are recognised:

1. At the mid-ocean ridge margin of a lithospheric plate new material is being injected into the centre of the spreading zone as the plates on either side move apart – this is known as a *constructive* margin.

2. Where island arcs, trenches and fold mountain belts occur there is a convergent movement of the plates

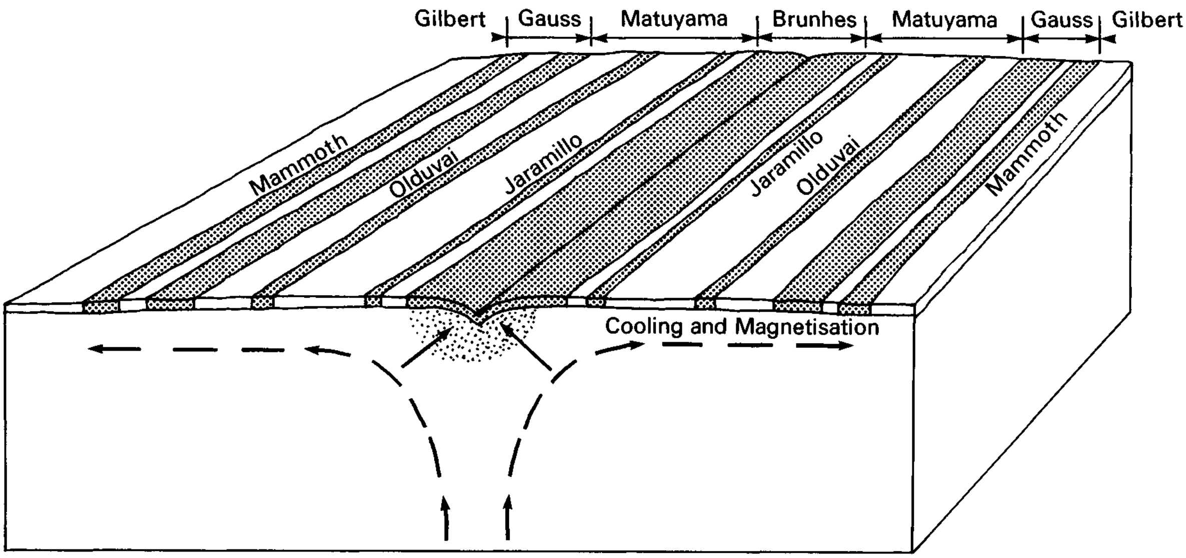

Figure 2.7. As new sea-floor material is produced at the spreading centre, it takes the polarity prevailing when it cools. The names Brunhes (normal), Matuyama (reversed), Gauss (normal) and Gilbert (reversed) refer to periods when polarity alternated during the past 4 million years.

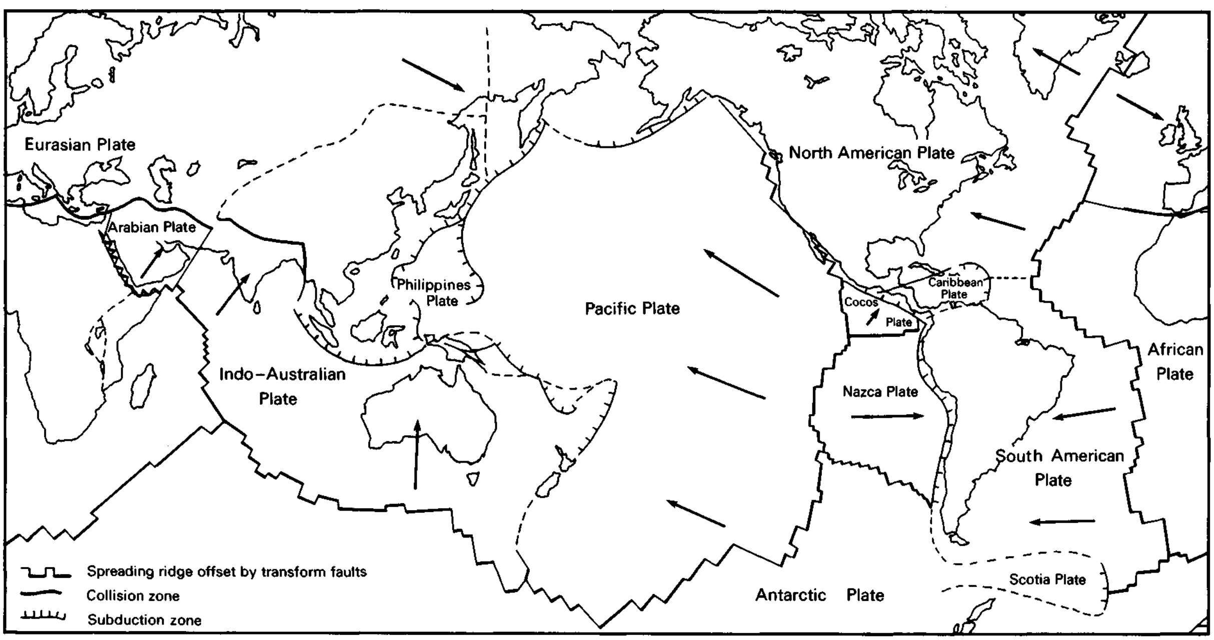

Figure 2.8. The major lithospheric plates of the Earth.

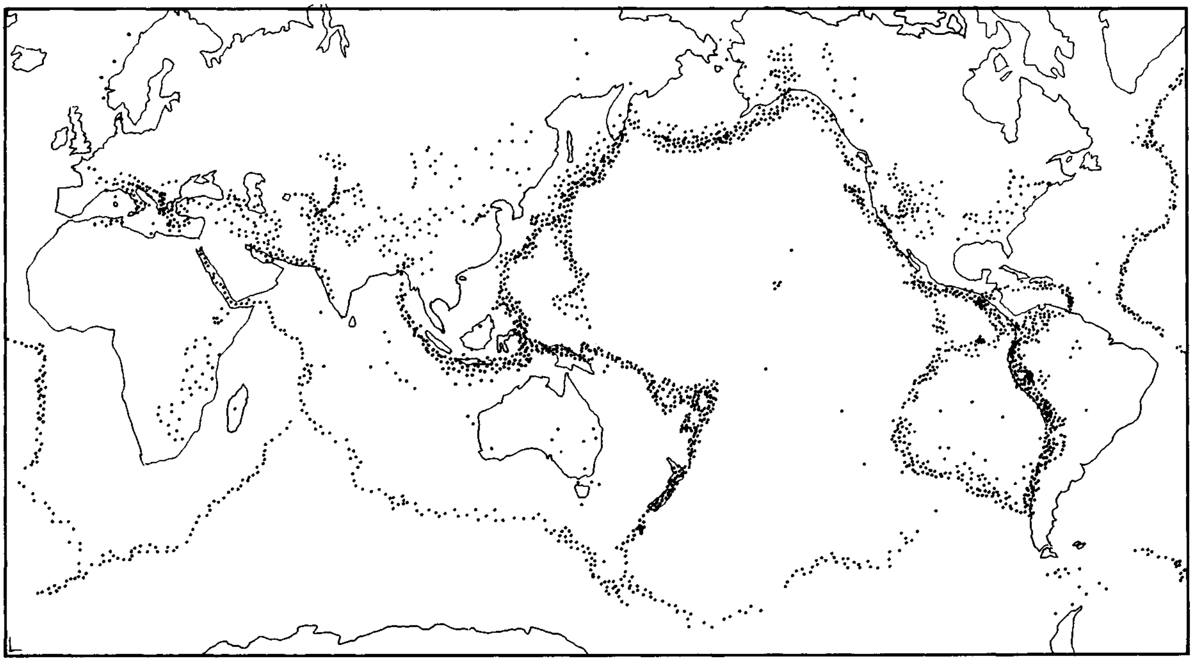

Figure 2.9. A map showing the location of major earthquakes outlines the major lithospheric plates.

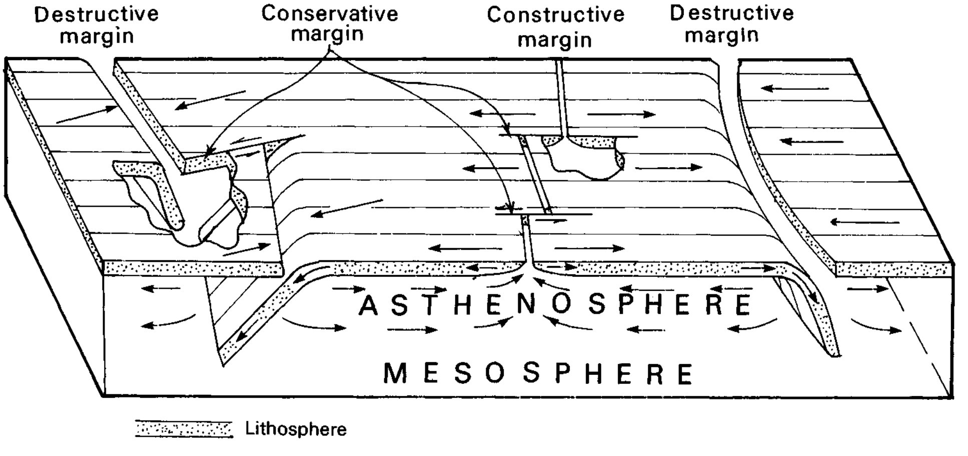

Figure 2.10. Types of plate boundary.

and the margin of one plate is being pushed down (subducted) into the asthenosphere – this is known as a *destructive* plate margin.

3. Where the plates are moving past each other, as along the famous San Andreas fault, and other transform faults which cross the spreading zones of the mid-oceanic ridges, lithospheric material is neither being created nor destroyed and so these margins have been called *conservative* margins.

The margins of the Atlantic Ocean were formed as the North American and African/European plates moved apart. Hence the name *Atlantic* or *trailing* margins are used. Around the Pacific the margins are mainly destructive with the plates moving together. These are referred to as *Pacific* or *collision* margins.

These names simply describe a number of different situations where the lithospheric plates interact. As the ocean-floor material is different from the material of the continents, it must be expected that the interaction of the plates would be different:

Simple subduction: the simplest case occurs where oceanic material meets continental material, as is taking place in the Andes. As continental material is so light, the denser, oceanic Pacific plate is being subducted beneath the South American plate where it is melted as it descends into the asthenosphere, so providing magma for volcanic activity.

Island arcs: these are a characteristic of the western Pacific Ocean and reflect a complex situation which is not altogether understood. A deep sea trench lies alongside a single or double arc of islands, the inner arc usually being volcanic. Island arcs differ in complexity for they are not all backed by continental materials as occurs in the Indonesian arc. In some cases oceanic material is in collision with oceanic material, as occurs in the South Sandwich arc of the south Atlantic. In the Philippines it is thought two arcs have collided to give the particular structures of that group of islands.

Continent to continent: where the Indian plate meets the Asian plate the Indian plate has been thrust beneath the Asian plate to give a double thickness of continental crust. A similar, but not so spectacular situation occurs in the mountains of Armenia where the Arabian plate is thrust beneath the Eurasian plate.

Within the lithospheric plates lines of weakness are indicated by a pattern of rifting seen in all continents, but particularly in the rift valleys of east Africa. In the past, fragmentation of Gondwana also seemed to have taken place, by rifting along similar lines to the east African rift valley with typical Y- or triple-junctions. This rifting was preceded by intrusion of alkaline volcanics which caused the doming of the area, and the extrusion of basaltic lava flows. It is uncertain whether the African rift valleys are a failed spreading centre. In many cases two arms of the triple junction are successful in developing a spreading centre and one arm fails; this failed arm is known as an aulacogen.

In the process of continental growth, the results of successive mountain-building episodes (orogens) have been attached to the older cratons of basement complex. In some cases materials of different ages are very firmly attached, but in other cases the line of weakness between them continues to be the seat of earthquakes.

Although the theory of plate tectonics has been widely accepted in the earth sciences and it provides answers to many of the problems of global tectonics, it still does not answer all of the questions. One such problem is the disparity between the length of the spreading centres compared with the length of the trenches where material is consumed. Similarly the pattern of earthquakes is not always consistent with the ideas of subduction, and it is apparent from the North American continent that it is riding over the margins of the Pacific plate regardless of the underlying structure. The link between mountain building and plate tectonic theory is not strong and the idea of compressive folding is losing ground to ideas of gravity sliding in the production of nappes and other folded structures seen in Alpine-like mountains. The simple model of a limited number of large lithospheric plates is breaking down as it is found that there are many micro-plates which are equally important in the determination of the large-scale morphology of the Earth.

Up to this point in the discussion of plate tectonics the size of the Earth has been assumed to remain constant. However, this may not be a correct assumption. It has been suggested that many of the problems of interpretation could be solved if the continents could be arranged on a smaller globe. The pattern of spreading outwards from the Atlantic, Indian and Southern oceans on an Earth of constant size suggests that much more compression should exist around the Pacific Ocean. In fact behind some of the island arcs, back arc basins have subsidiary spreading centres showing that the Pacific, too, has expanded. Although virtually impossible to calculate, it appears that more new sea floor is being created at spreading centres than is being consumed in the subduction zones. The roughly poly-

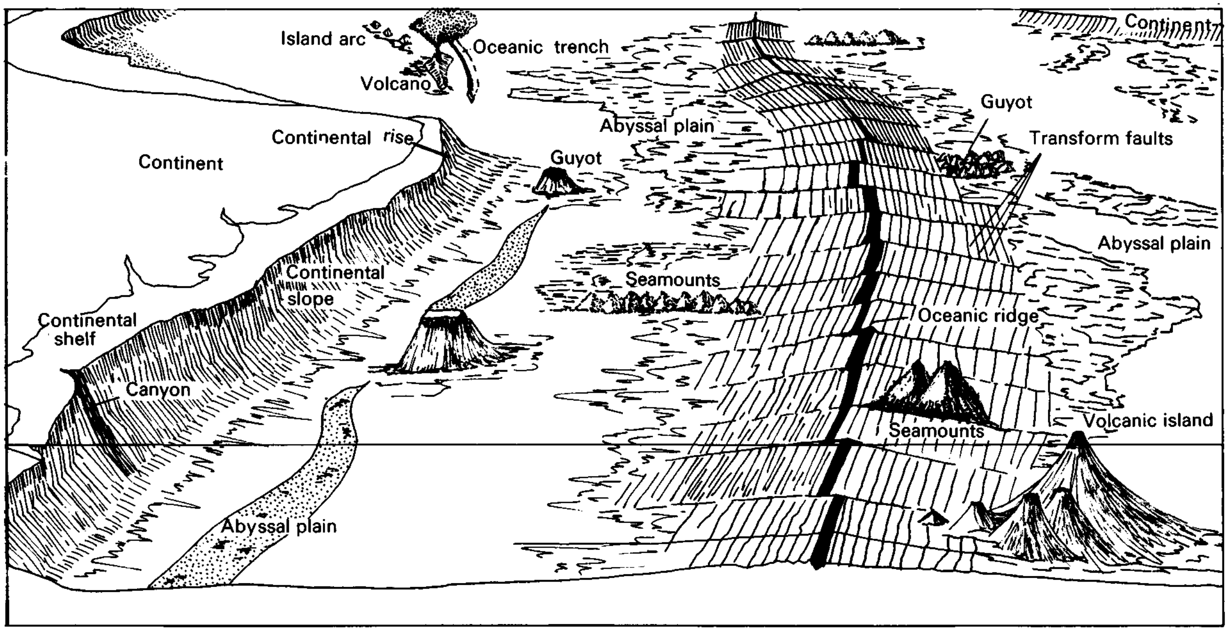

Figure 2.11. Features of the ocean floor.

gonal shape of the lithospheric plates is consistent with an expansion of the earth and, except for Antarctica, all the other plates have migrated northwards from the Southern Ocean spreading centre, again giving support to the idea of an expanding Earth. With these cautionary words, a consideration of the origin and development of the ocean floors and the continental areas follows in the next section.

Origin of the sea floor

It has been demonstrated that ocean-floor rocks are different from the continental rocks. In general, this difference can be expressed by describing the sea-floor rocks as basaltic and the continental rocks as granitic. The geological origin and development of sea floor and continents is markedly different, so it is convenient to discuss them separately.

Recent discoveries have shown that the morphology of the ocean floor reflects a dynamic state and not a static situation. As the role of the sea floor in the broad pattern of the Earth's morphology is seen now to be of basic importance, it is clearly the most suitable place to begin a study of world geomorphology. There are three major elements in sea-floor morphology: the spreading centres; the ocean basins; and the trenches. Each of these features plays an important part in the understanding of the global geomorphological development.

The spreading centres

The Atlantic, Indian and Southern oceans are characterised by mid-oceanic ridges which mark the location of spreading centres (Figure 2.11). The Pacific Ocean is slightly different as the line of the spreading centre swings from the south-eastern Pacific and eventually passes on to land in California as the San Andreas fault, eventually passing back to the ocean floor again off the coast of north-western USA. The only other major land area where the spreading centre emerges is in Iceland which lies astride the mid-Atlantic ridge.

As revealed by surveys, the form of the mid-oceanic ridge is of parallel strips of material extruded on either side of the spreading centre. The overall height of the mid-oceanic ridge depends partly upon the rate at which material is being extruded and partly upon the rate of spreading because away from the spreading centre the newly extruded sea-floor material settles back into the Earth's crust. If spreading is rapid, the mid-oceanic ridge will be broad with gently sloping sides, but if spreading is slow, the slopes of the ridge are much steeper, as in the South Atlantic. In some cases it has

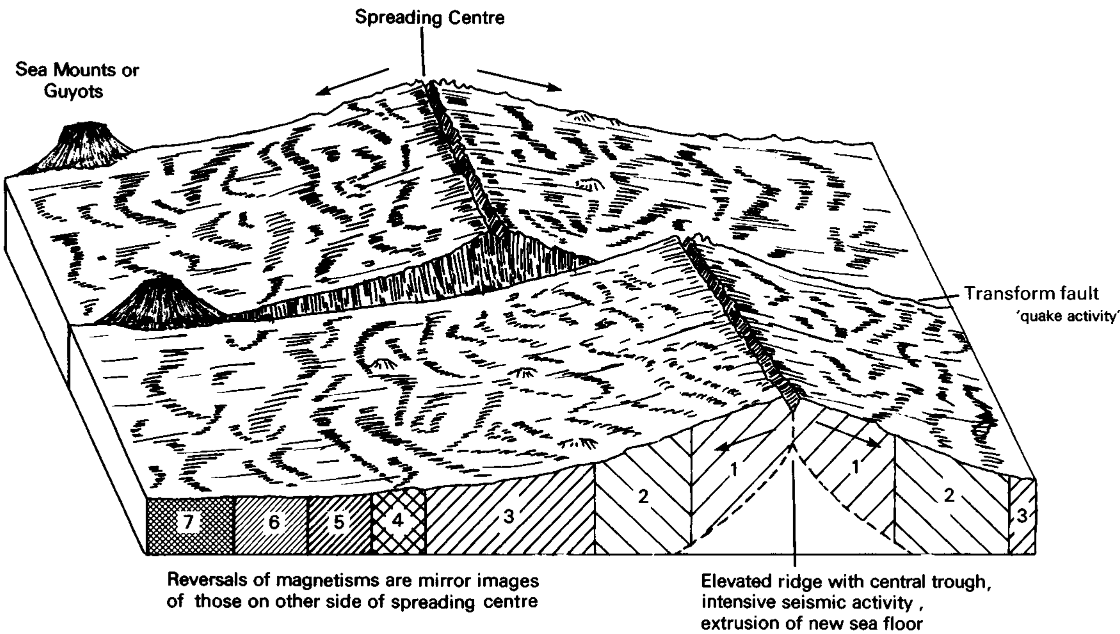

Figure 2.12. A spreading centre with a transform fault.

been possible to distinguish a rift-like valley between the two sides of the spreading centre; in Iceland it is 45 km wide, and in the Indian Ocean the central rift valley is 300 m deeper than the ocean floor on either side.

The mid-oceanic ridge is not continuous but comprises a succession of segments where it has been shifted out of line by transform faults oriented at right angles to the ridge. As Figure 2.12 shows, this can lead to situations where adjacent segments of the Earth's crust are moving in opposite directions. Where this occurs earthquakes are particularly common and they are often accompanied by volcanic activity. Occasionally, the amount of volcanic outpourings is sufficient to raise the level of the lava above sea level to form one or more volcanic islands. It is noticeable that islands further from the spreading centre are larger than those close by. This fits the general picture because the oldest volcanoes have obviously continued to grow as they have produced much greater quantities of lava over the longer period of their existence. Most volcanoes cease to be active after a period of 20 to 30 million years and only a few, such as the Canary Islands, remain active for up to 100 million years.

Extinct volcanoes on the sea floor are referred to as guyots or seamounts, many of these do not grow sufficiently to appear above the sea surface as islands and even some of those which did become islands later sank below the sea again as the crust settled away from the spreading centre. Often guyots are flat-topped as wave action has trimmed their summits. As they gradually sink out of sight these guyots sometimes form the foundations of atolls. The guyots are carried along on the tectonic plate and they are ultimately consumed when the edge of the plate passes into a subduction zone. One such guyot has been discovered on the side of the Tonga trench, appropriately tipped over as it is being carried downwards before finally disappearing for ever; another sits on the floor of the Aleutian trench, about to be consumed.

The ocean basins

Away from the spreading centres, the ocean floor gradually descends to the level of the ocean basin floor, alternatively called the abyssal plain. This descent from the crest of the mid-oceanic ridge, at about 2000 m, to the abyssal plain at 5000 m takes place in a series of steps associated with successive outpourings of new material from the spreading centre. As new material is intruded along the line of the spreading centre, the previous intrusions are pushed further and further apart. As each intrusion became magnetised in sympathy with the

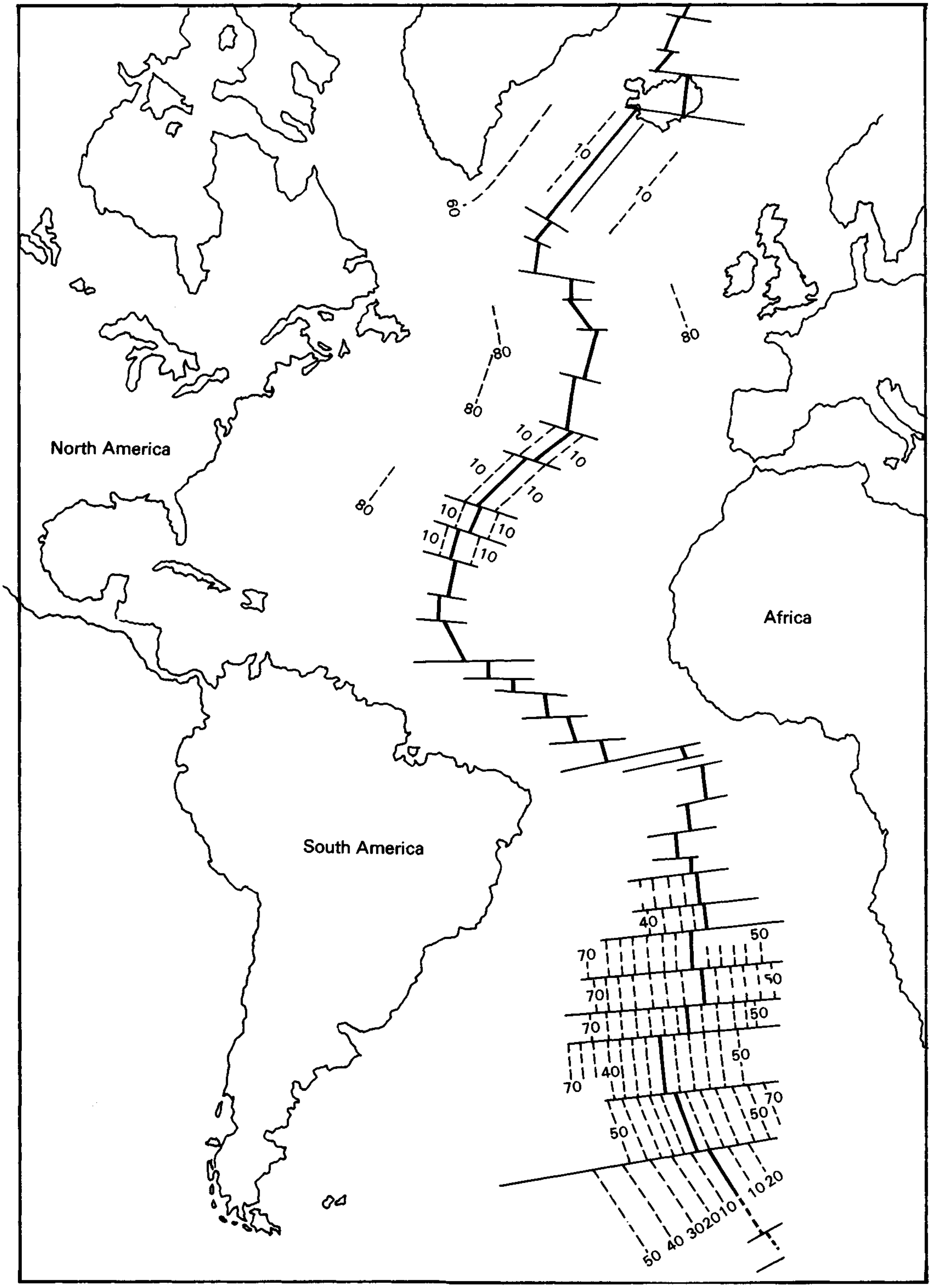

Figure 2.13. The mid-Atlantic ridge with parallel strips of new sea floor. The age of these strips on either side of the spreading centre is given in millions of years.

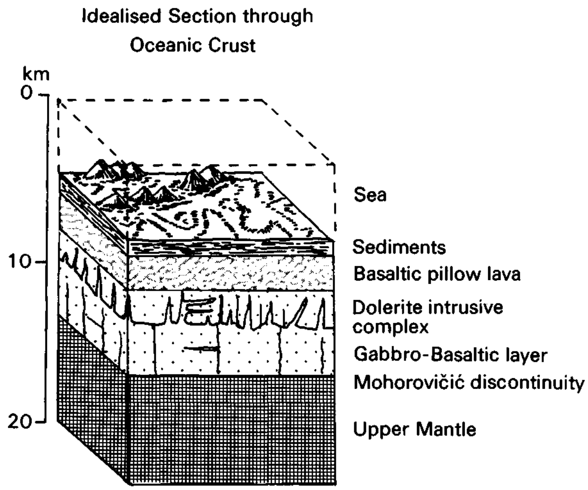

Figure 2.14. Idealised section through the oceanic crust.

Earth's contemporary magnetic field, it follows that the changes in polarity observed in the rocks are related to changes in the Earth's magnetic characteristics. Surveys have shown that this theoretical picture is correct, and that the sea floor is made up of a sequence of parallel strips of rock some of which have reversed magnetism. As polarity has changed many times in the past and at varying intervals, it is possible to compare the pattern of alternately magnetised strips from different oceans. On all ocean floors the evidence is the same, areas of new sea floor are symmetrical and the alternately polarised bands are found to agree in age and direction of magnetisation (Figure 2.13).

The floor of the ocean basins appears to have three major layers. Overlying the mantle and the asthenosphere (or weak plastic layer) is the 'oceanic layer' composed of a basic igneous rock complex with many doleritic dykes passing downwards into layered gabbros, making a layer 5 km thick. Upon this is a second layer, 1.5 to 2.0 km in thickness, composed of basaltic pillow lavas which have been extruded under water and rapidly cooled. Adjacent to continental areas, this, volcanic layer may become interstratified with consolidated sedimentary rocks such as limestone and shales (Figure 2.14).

The trenches

If new sea-floor material is constantly being intruded along the lines of the spreading centres and the size of the Earth remains the same, it follows that an approximately equal amount of material must be destroyed or absorbed back into the deeper layers of the Earth's crust. This takes place in the deep oceanic trenches.

In the nineteenth century a British oceanographic survey vessel found depths greater than 8000 m (24 000 ft) near Tonga in the Pacific Ocean. Subsequently, it was found that the deepest parts of this abyss was 12 000 m (35 000 ft) deep and that it occurred in a long narrow V-shaped chasm where the sea was approximately seven times as deep as the Grand Canyon. Other trenches were subsequently found and in most cases they were found to be slightly over 12 000 m deep. Characteristically, these deepest parts of the oceans were not in the middle but around the periphery, near the Aleutian Islands, Japan, the Marianas Islands, the Philippine Islands, Java, Peru, Chile and Guatemala (Figure 2.15). Significantly, there is no trench off the western coast of the United States, but the structures associated with the San Andreas fault indicate a completely different geological situation. In the Atlantic Ocean, trenches are not so common, only being found in association with the island arcs of the West Indies and the South Sandwich Islands. The Indian Ocean has a trench south-west of Sumatra and extending towards the Andaman and Nicobar Islands.

The trenches are associated with negative anomalies of gravity and with earthquakes and volcanic activity on their landward side. The amount of heat flowing from the interior of the Earth in these regions is less than normal, suggesting that there might be a downward movement of cool rock which would reduce the outward flow of heat. As these trenches are the deepest part of the ocean, it might be thought that they would have an accumulation of sediment in them, but this is not so; only when trenches cease to be active do they accumulate sediments to any extent. It is not thought, therefore, that trenches develop into geosynclines, as the latter are characterised by large sediment accumulations.

The active role of the deep sea trenches concerns the leading edges of the tectonic plates. Previously it has been described how new sea floor is created at the spreading centres; it is also obvious that an equal amount must be removed in some way. As a crustal plate grows, its leading edge is destroyed at the same rate by reabsorbtion into the deeper layers of the crust. Where tectonic plates are moving together at speeds of more than 5 cm per year, one plate normally slides beneath the other and is consumed in a subduction zone

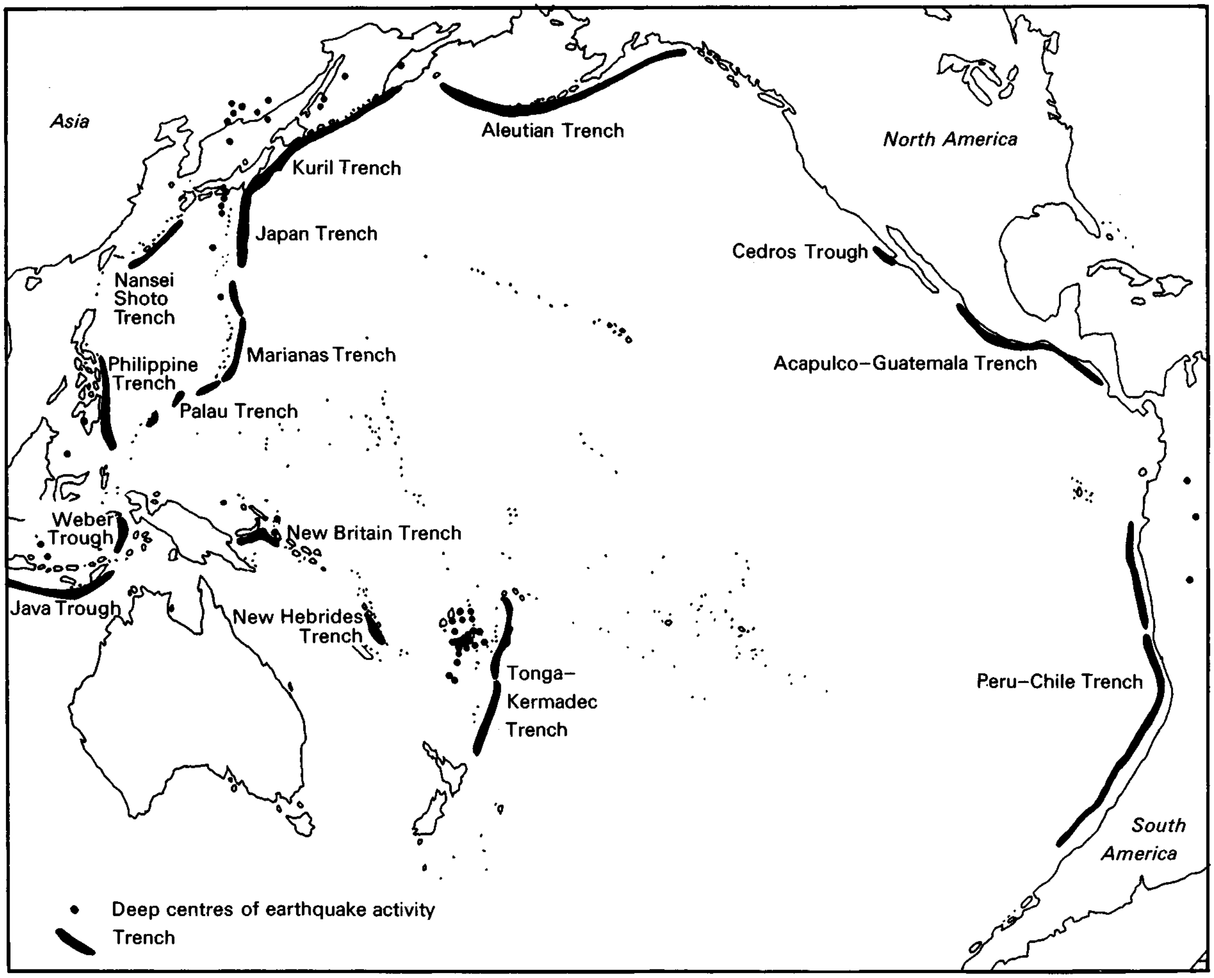

Figure 2.15. Trenches of the Pacific and location of deep earthquake foci. (After Fisher and Reville, 1955.)

(also known as a Benioff zone). The leading edge of the plate passes downwards into the asthenosphere and this zone is usually marked by many earthquakes and by intense volcanic activity (Figure 2.16). At lower speeds of approach it is possible for two colliding plates to buckle at the edges and produce fold mountain ranges between the two advancing plates.

Origin of the continental areas

Uniformitarianism is a principle of geology which, put simply, states that the present is the key to the past. Observation of present-day processes leads to an understanding of what has happened in geological history throughout which a similar set of processes has operated. It is quite logical that if erosion takes place in one locality, there must be a corresponding deposition of material elsewhere.

For many years now, it has been understood that eventually all eroded material becomes deposited in downward-sagging belts of the Earth's crust known as *geosynclines*. This name was first given to these features by Dana in 1873. At first it was thought that the weight of sediment would initiate a downwarping, but this is now thought not to be the case and an independent downwarping occurs first, only to be reinforced later by the weight of accumulating sediment. The downward movement of the crust to accommodate the additional

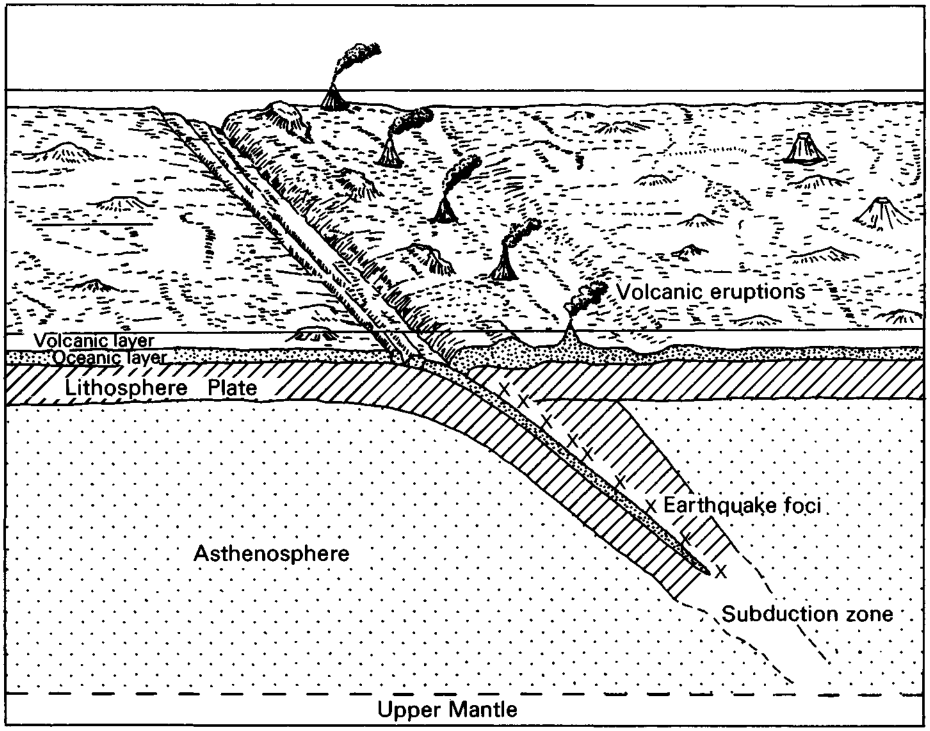

Figure 2.16. Section of deep sea trench with subduction zone and location of earthquake foci.

load of sediment is relatively slow. It has been calculated that 12 000 m of sediment accumulated between the Cambrian and the Permian in the Appalachian region and that this represented accumulation at the rate of 10 cm in 2500 years on average. It was assumed that as the downward-sagging sediments reached deeper and deeper into the Earth's crust they would be subject to pressure and heat which would produce metamorphic rocks such as schists and gneisses. Finally, movement of the forelands on either side of the geosyncline brought compression of the geosyncline resulting in uplift, folding and faulting. Igneous activity accompanied this activity with volcanoes and the instrusion of sills and dykes. In the deeper parts of the geosyncline plutonic intrusion invaded the sedimentary rocks to give granitic cores beneath the mountain ranges. These were only revealed subsequently when the mountains were eroded down to their roots.

Thrust-faulting or nappes (and less complicated folding) are greatest on either side of the geosyncline whereas in the centre considerable median masses may be uplifted, or in some cases downfaulted (Figure 2.17). The Tibetan plateau and the Hungarian basin are examples of uplifted/downfaulted but relatively unaffected land masses which were affected by the Alpine orogeny. The Tyrhennian Sea is an example of a large downfaulted basin. The ideal picture of a geosyncline given in many textbooks suggests a symmetrical upthrusting resulting from an inward movement of the forelands on each side. However, these movement are not always evenly matched. In the case of the Tethys geosyncline it appears that the African plate moved against the European foreland over which the northern folds have been thrust.

Although the concept of plate tectonics has revolutionised our understanding of the ocean floor, it is perhaps not quite so obvious how the theory can be related to the origin and growth of the continental areas. Fortunately, many aspects of the geosynclinal theory previously described can be linked to the ideas of plate tectonics to give a satisfactory explanation of the growth of continental masses.

Radioactive dating of the basement rocks indicates that there are nuclei or core areas in the continents

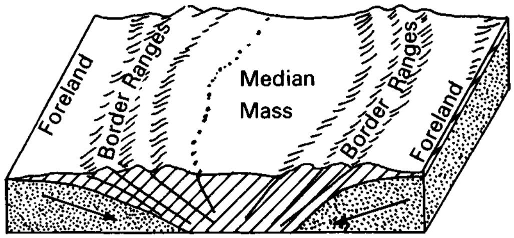

Figure 2.17. Diagram of a mediean mass (zweisengebirge.)

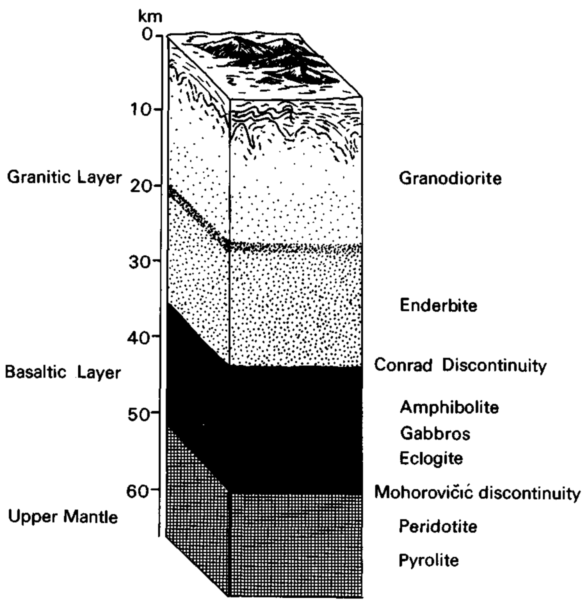

Figure 2.18. Idealised section through continental crust.

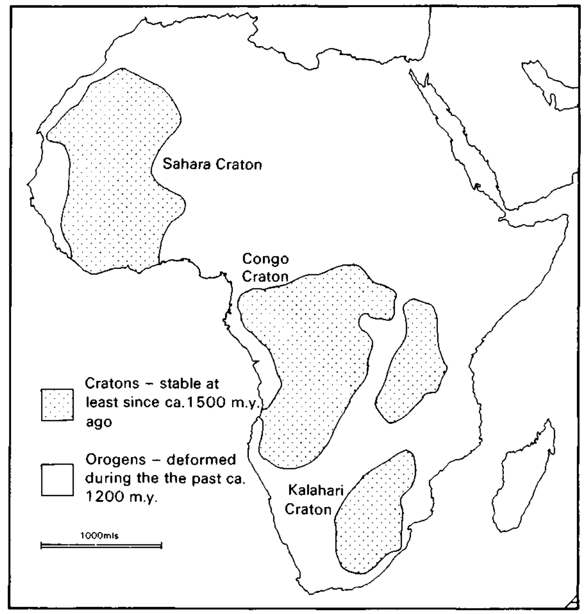

Figure 2.19. Cratons of Africa.

which are more than 2000 million years old, around and upon which successively younger deposits have accumulated. The landmasses have a different structure and composition from the ocean floor, already described. Overlying the mantle and the Mohorovičić discontinuity is a layer of basaltic composition similar to that found beneath the oceans (Figure 2.18). It has been described in Chapter 1 how this layer crops out only at a small number of locations and it appears to be formed of amphibolite, a metamorphosed form of basalt. Normally, it lies between 35 and 50 km below the surface except for the few fragments which have been brought to the surface in the process of mountain building.

The upper part of the continental crust lies above the Conrad discontinuity; it is composed of granitic rocks which extend to a depth of 35 km. These rocks are comprised of 92% igneous and metamorphic rocks with only 8% sedimentary material such as limestones, sandstones and shales, which lie near to the surface. The continental material lying above the Conrad discontinuity is formed from a combination of structurally complex, older shield areas, bordered by younger, intensively-folded sedimentary rocks.

Approximately 80% of the continental areas are underlain by the older, Pre-Cambrian rocks, which are called the basement complex. These oldest parts of the continents have grown by accretion as tectonic activity metamorphosed former sediments into crystalline rocks. Growth did not take place uniformly, but in phases associated with mountain building and igneous activity, which reached peaks around 2700, 1800 and 1000 million years ago. Most of the rocks of these older shield areas have experienced pressures and temperatures unknown in the younger fold mountains. The approximate ages of different parts (cratons) of the basement complex of Africa are shown in Figure 2.19.

Some parts of the basement complex are covered extensively with undeformed or slightly deformed sedimentary rocks. Others have accumulated in deep persistent downwarps which extend to 15 km depth below the surface. Where the Pre-Cambrian basement complex is exposed at the surface, it can be seen to be both structurally and chemically complex. Intense fold-

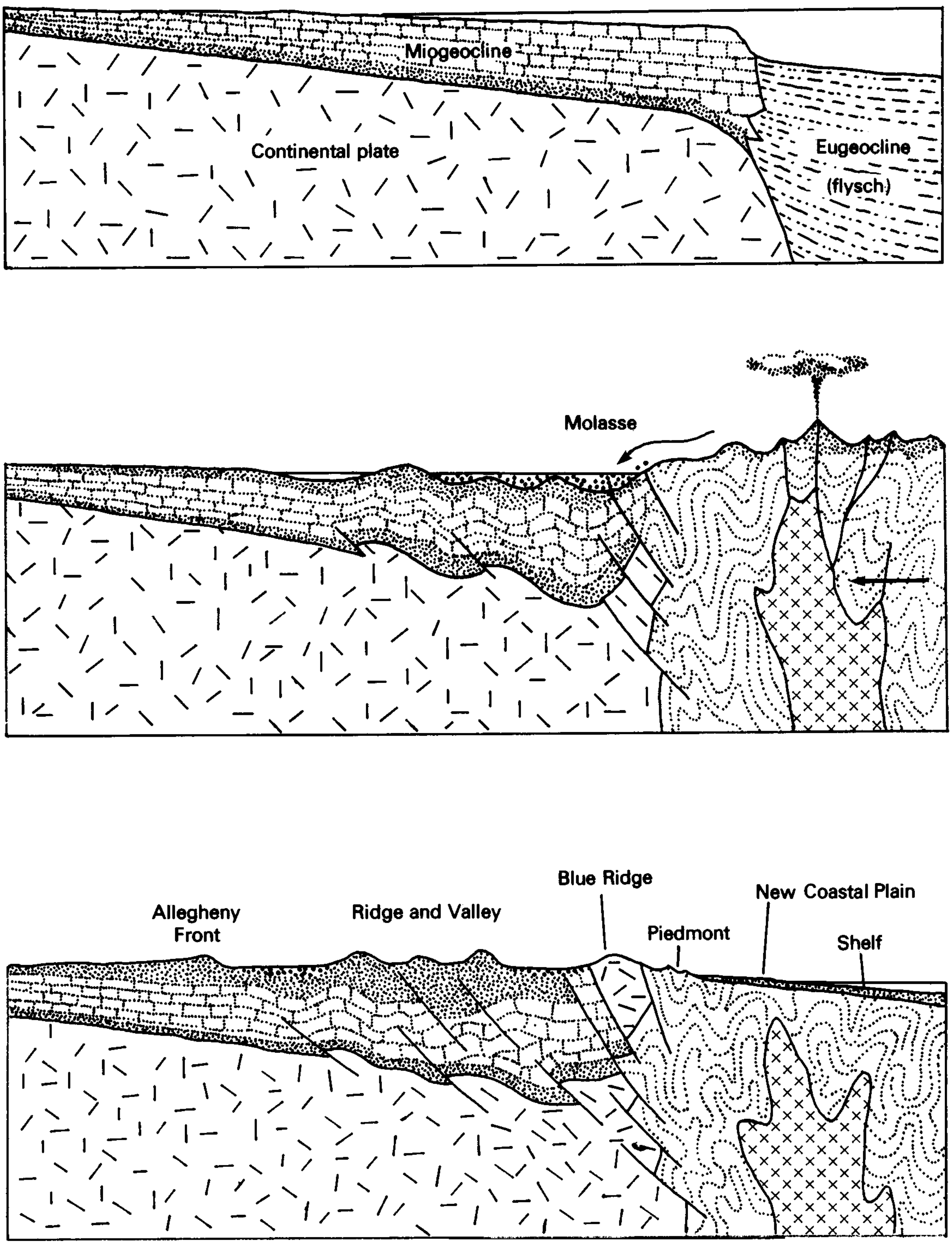

Figure 2.20. Eugeosyncline and miogeosyncline couplet.

ing is characteristic and may be associated with acid or basic igneous rocks, the latter possibly being former pieces of the oceanic floor caught up in orogenesis. Rocks from the basement complex, too, can be caught up in later orogenic activity and may form significant parts of the roots of mountain ranges.

An earlier view of orogenesis was given at the beginning of this section in the description of a geosyncline. The theory left many points unanswered which the recent discoveries associated with plate tectonics helped to answer. Recent observations have led to the suggestion that there are two parts of a geosyncline (a geosynclinal couplet), lying side by side and each playing a distinct role (Figure 2.20). According to Deitz (1972) deposition of shallow-water beds occurs in a miogeosyncline (lesser geosyncline) where crustal downwarping occurs at the edge of a continental mass. These sediments increase in thickness seawards and end at the edge of the continental shelf. Alongside the continental margin is the eugeosyncline (true geosyncline), comprising a wedge of sediments accumulated on the ocean floor and embanked against the continental rise. The sediments of the eugeosyncline are derived from muddy suspensions, known as trubidites, which have the appearance of thinly-bedded, poorly-sorted sands and silts interbedded with clays. Such sedimentary rocks have also been referred to as graywacke or flysch.

One of the most likely places for a geosynclinal couplet would be on the trailing edge of a lithospheric plate. It is suggested that as new sea floor was intruded an initial sagging took place into which the deposit of the eugeosyncline began to accumulate. Once started, subsidence continued under the weight of the sediments as isostatic compensation took place. On the landward side, this downward flexing provided the continuing shallow water conditions observed in the miogeosyncline. Altogether it is thought that a depth of up to 15 km of sediment could accumulate.

As the ocean basins are not fixed, but continually altering according to the lithospheric plate, it is possible that a subduction zone could be initiated by the deeply sagging eugeosyncline. Then as the ocean floor advanced towards the landmass, the sedimentary content of the eugeosyncline would be crumpled against it as well as being thrust deeply into the Earth's crust. Isostatic readjustment would eventually follow to raise the folded material as a mountain mass.

Alternatively, the eugeosyncline could be squeezed between two approaching continental masses. Once again crumpling would occur and the sediments would be strongly compressed, leading to the production of metamorphic rocks and to a thickening of the upper layer of the crust. Isostatic readjustment would then come into operation as in the previous case, associated with volcanic intrusion and emplacement of batholiths in the core of the folded sediments.

The miogeosyncline with its sedimentary deposits would be less strongly compressed and only affected by volcanic intrusions. The degree of folding would be greatest at the seaward edge of the miogeosyncline and would decrease inland until unfolded beds mantled the basement rocks formed earlier. As compression and mountain building took place, contemporaneous continental deposits of conglomerates, sandstones and shales, known collectively as molasse, accumulated to cover partially the slightly folded miogeosyncline beds as erosion attacked the rising mountain chain.

The theory of plate tectonics proposes that the surface of the Earth is composed of eight major lithospheric plates and a number of smaller areas, known as micro-plates. The major plates are the Eurasian, African, Indo-Australian, North American, South American, Pacific, Nazca and Antarctic plates. The micro-plates include smaller sub-continental areas such as occur in the Caribbean, south Pacific and Anatolian areas.

This account of world geomorphology attempts to discuss the geomorphology of the lithospheric plates which form the primary sub-divisions of the Earth's morphology. Each major plate has a submarine and a terrestrial component. Knowledge of the terrestrial geomorphology of each major plate varies greatly in detail; of the submarine geomorphology, which is less easily observed, only the briefest outlines are known.