1 Major features of the Earth and plate tectonics

The father of geology, James Hutton, in the late eighteenth century provided the insights which led nearly a century later to the first understandings of how mountains are constructed and what causes them. In the nineteenth and early twentieth centuries Lapworth, Peach and Horne, and Clough in Britain, and Argand, Bertrand, Heim and others working in the Swiss Alps, revolutionised our understanding of what the German geologist Kober called 'orogens' and of the process of orogenesis, the building of mountains.

To understand the significance of orogens, it is necessary to know something about plate tectonics, which has been remarkably successful in explaining many of the features of the Earth. In particular it deals with large-scale dynamic processes in the planet. Plate tectonics developed from the preceding ideas of continental drift, but in essence originated from an idea put forward in the 1960s by H. H. Hess. Hess postulated a surprising concept: that the ocean floor is in motion and is older as one moves away from submarine mountains known as mid ocean rises: for this reason the model became known as sea-floor spreading. The ocean floor is like a giant conveyor belt, and the interesting question is, where does it go? What this idea meant was that, for the first time in the history of geology, attention was turned on the oceans rather than the continents.

This new approach brought about a revival of the older idea of continental drift, which proposed that the continents over geological time have not been fixed in position but have drifted across the surface of the Earth. Half a century ago, many thought this idea to be nonsense. In Britain, the great Arthur Holmes, who had already provided the first quantification of geological time and the age of the Earth in his famous book of 1944 (see also Holmes 1928, 1929), made an eloquent case for continental drift, but most geologists were strongly opposed to the idea, pointing out there was no mechanism for such motion. However, in 1928 Holmes had outlined a mechanism for drift by invoking convection cells in the mantle which dragged the crust along, a view which anticipated Hess's discovery. Hess's sea-floor spreading model and the then new powerful technique of palaeomagnetism swung geological opinion round into acceptance of mobile continents which have moved over time, albeit through the creation and destruction of intervening oceans rather than by ploughing their own furrows across the Earth's mantle.

A spectacular consequence of the nineteenth-century work on continental tectonics was the discovery of thrust faults. There was the almost simultaneous discovery in the 1980s of the Moine thrust in Scotland and the Glarus thrust in the Swiss Alps, leading to the realisation that large bodies of rock can be transported along low angle faults horizontally over other rocks, sometimes for great distances. The existence of mountain belts has long been known, if only because they may be conspicuous features, but their causal origin and nature has only become clear in the past 50 years, following the discovery of plate tectonics.

In this book the term orogen is used for the narrow but long belts of crust which have been deformed mainly by compressional stresses in the process of orogenesis. It is better to avoid the term mountain belt, because many ancient orogens are rather poor mountains in the topographic sense! What follows is a brief account of the plate tectonic model, starting with a review of the Earth's major features including the crucial differences between oceans and continents.

Plate tectonics

Oceans make up 75% of the Earth's surface and they are young, say <200 million years (Ma). Their structure is simple. In contrast the continents are sometimes as old as *c*.4.0 billion years (Ga), and are structurally complex. Oceanic crust is uniform, between 3–10 km thick and mainly made of basaltic igneous rocks. Continental crust is, on average, *c*.35 km thick. Being largely composed of silica-rich, iron- and magnesium-poor rocks, it is less dense than ocean crust. On average the continental crust is regarded as intermediate in composition – not granitic, not basaltic but in between (andesitic). But in orogens continental crust can be twice the normal thickness: for instance, it is *c*.70 km thick under Tibet. On the other hand in rift zones like the Basin and Range of the western United States the crust is thinned. Compression and extensional tectonics are common on the continents and in rocks of all ages. The upper levels of continental crust are composed of sediments which are sometimes metamorphosed. The middle levels are composed of high-grade metamorphic rocks including migmatites which result from partial melting. The lower levels are composed of granulite facies gneisses with mafic and silicic plutons.

The oldest rocks on the continents are seen in so-called Precambrian Shields, specifically in cratons. These make up the central regions of most continents such as India, Africa, Asia and America. The rocks in the Shields are more than 600 Ma and stretch back to the oldest dated rocks at *c*.4 Ga. Within the Shields, cratons are those regions of continental crust that experienced their last significant crust-forming or generation in the Archaean, prior to about 2500 Ma. In these areas we see high-grade metamorphic rocks, comprising gneisses which were formed at great depths in the Earth and then exhumed at the surface, as well as magmatic belts and sedimentary–volcanic belts known as greenstone belts and their accompanying deformed ‘granitoids’ which are dominated by tonalites and related felsic intermediate rocks.

The greenstone belts are interpreted as ultramafic to mafic volcanic igneous complexes accompanied by more felsic volcanic centres. In addition, sediments such as quartzite, carbonate and ironstone are found, and these are witnesses to the presence of seas, even up to at least 3700 Ma ago in the case of the Isua greenstone belts of west Greenland. The origins and tectonic settings of these ancient rocks remain controversial, but for some geologists, applying the famous Huttonian principle that the present is the key to the past, the rocks can be interpreted in terms of plate tectonics. If so, the implication is that, as today, oceans and continents existed in the Archaean. The apparent problem is that the present oceans are very young. What, then, has happened to the ancient floors of the oceans? To answer this we need to know more about the oceans.

Mid Ocean Rises

Although much of the ocean floor is flat and featureless, there are conspicuous elevated regions. These are called Mid Ocean Rises, although not all are positioned centrally in an ocean. These ocean rises are long linear features, up to 40,000 km long, 2.5 km high and 2000 km wide. This means that they are the biggest mountain ranges on Earth. That they are special places in the oceans is shown by the fact that the heat flow at the rises is much higher than is normal for oceans. They are hot because basaltic magmas, dykes and lavas are being intruded and extruded there. The space for the magmatic rocks is provided by the normal faults which are structures associated with extension.

In the plate model, the Mid Ocean Rises are places where new ocean crust is actively being created. This continuous creation of new crust poses a problem. If the Earth does not expand to accommodate the extra crust, where does it go? This is where sea-floor spreading comes in, as does the analogy of a conveyor belt. The ocean floor moves away from the Mid Ocean Rises and disappears – where? At the margins of oceans, another link in the chain of events is provided by the ocean trenches which can be as much as 12 km deep, where the ocean floor plunges beneath the continents. The process is called subduction. Thus there is a balanced system of creation of new crust and its eventual disappearance. Long before the discovery of plate tectonics, subduction zones were recognised by study of patterns of shallow, medium and deep foci for earthquakes, and were named Benioff zones. The Benioff zone is essentially a thrust along which ocean crust slides down to great depths beneath the continents. Subduction zones are associated with curvilinear zones of volcanoes, termed island arcs, situated above the Benioff zone. Good examples are the Indonesian islands and the Japanese islands. The volcanoes show that the activity of the Benioff zone has induced melting of rocks at depth and the rise of magma to the Earth's surface.

Plate boundaries

We can now define what is meant by a plate. In the oceans a plate is the lithosphere forming ocean floor between the Rises and the subduction zones. Some plates also carry continental crust. The boundaries of a plate are subduction zones, Mid Ocean Rises or transform faults (see later). The plate boundaries are termed *divergent* where the plate motion is away from the boundary, as at a Rise, and *convergent* where the motion is towards a boundary, as at a subduction zone. At the present the Earth is covered by about seven or eight major plates and two minor plates.

Magnetic anomalies

The whole system is moving and the rate of plate motion can be measured by using the Global Positioning System (GPS). But the first timescale for plate motion and indeed the final confirmation of the reality of sea-floor spreading came from studies of rock magnetism. Earlier we indicated that palaeomagnetism provided a confirmation of continental drift. This is because certain rocks can capture the orientation of the Earth's magnetic field at the time and place of their formation and retain this as a memory. Because the magnetic inclination varies from the equator to the poles and is dependent on latitude it is possible to show that rocks have wandered across the Earth's surface. The principles of rock magnetism can also be applied to the problem of sea-floor spreading.

Mapping the magnetic intensity of the ocean floor using sea-borne magnetometers revealed a strange feature. The intensity varied in a systematic way, so that the maps of magnetic intensity showed over large areas of ocean a striped pattern of alternating high and low intensity, so-called magnetic anomalies. This was unexplained until Fred Vine and David Matthews spotted the truth in 1963: the variations in intensity reflected periodic reversals in the Earth's magnetic field, with north and south poles switching position. Rocks with reversed magnetism showed lower intensity whereas those with normal or present day polarity showed high magnetic intensity. The next step was to date the normal and reversed stripes of the ocean. At first sight the inaccessibility of ocean floors might seem to be an insurmountable problem, but there is a way round this involving the intricate correlation of the stripes from the oceans with a similar reversal pattern in dated rocks from the continents, the latter being easy to hand. From this arose a magnetic stratigraphy which dated ocean floors. The result was clear: the oceans were youngest at the Rises and aged towards the trenches. This is exactly what the conveyor belt idea predicted. From this work we can say that the rate of motion of plates varies from *c*.2 cm to *c*.18 cm *per year*. The former rate is often expressed as being about the same as the rate of growth of your fingernails.

The analysis of plate motion has been very thorough and involves consideration of plate motion on the curved surface of the Earth using Eulerian geometry. Another component of the ocean-floor spreading must be added – the transform faults that are needed to account for the interaction of the moving plates and to understand what happens at the end of a plate boundary. Motion along transforms is strike-slip. Transform faults are common features of ocean floors but they occasionally affect continental rocks, e.g. the San Andreas and Dead Sea transform faults.

Lithospheric plates

The final point is to consider the plates in three dimensions: in other words, how thick are they? The plate is composed of more than continental or oceanic crust because it includes the upper mantle. Chemically the mantle is quite unlike the crust because it is much richer in iron and magnesium and is made of distinctive rocks such as peridotites and lherzolites. The whole column of rock in a plate, that is the crust and the upper mantle, is referred to as the lithosphere. This model marks an important, indeed key, departure from the previous continental drift hypothesis which assumed that the continents moved independently, and this is crucial in the discussion of orogens. The base of the plate is the contact between the lithosphere and the underlying asthenosphere. The latter is mantle, and as we will see it is important in the study of orogens as a source of heat. Plate tectonics provides a broad framework and indeed a *raison-d'etre* for orogens.

Orogens and plate tectonics

Most orogens are sited on convergent plate boundaries, and the most familiar illustration of this is in orogens like the Alps or Himalaya, which have been formed by the collision of continents. Such collisions are inevitable in plate tectonics. Many but not all orogens mark the sites of ancient oceans which have closed completely as a result of plate motion. Examples are the Alps which formed during the closure of the Mesozoic Tethys Ocean and the Caledonian orogens which formed during the closure of the early Palaeozoic Iapetus Ocean. The history of the planet is one of ocean growth followed by ocean closure, a process called the Wilson cycle after Tuzo Wilson, the great Canadian geophysicist.

Rheological control over continental break-up

Where are the likely places in the continental crust for continental break-up? Krabbendam (2001) cited inherent strength differences between different orogens, and he emphasised that the relatively weak orogens serve as loci for continental break-up. One example is the way the split between America and Europe seems to have been controlled in part at least by the Caledonian orogen. Other stronger orogens have resisted being sites of break-up. For example the Urals, in contrast to the Caledonian belt, retain a strong mantle root, and are also strengthened by the presence of ophiolites and other mafic rocks.

Dewey and Bird classification of orogens

In 1970 Dewey and Bird gave a classification of orogens based on their settings in relation to plate boundaries:

1. The Andean-type belts, situated on continental margins above subduction zones where ocean crust is being subducted beneath continental lithosphere. The name is from the Andes of South America.
2. The continent–continent collision belts such as the Himalaya, resulting from the collision of India and Asia, or the Alps, which result from the collision of Europe and Africa.
3. The (island) arc–continent collisional belts such as in New Guinea, which are formed when an island arc collides with the adjacent continent as a result of plate reorganisation.

Examples of the three types of orogen will be given in Chapter 5. In addition a fourth type may be added – intracratonic orogens resulting from so-called far-field stresses transmitted through the continental crust from an active plate margin. The Neoproterozoic orogens in central Australia appear to have formed far away from a plate boundary and may be examples of this type.

Ancient plates and orogeny

The first three orogen types given above come from the orogenic belts formed in the past 50 Ma, but the classification has been extended to older belts. For example, the Early Palaeozoic Grampian orogen of Scotland and the Taconic orogen in North America are interpreted as arc–continent collision belts. Other parts of the Caledonian belt are viewed as continent–continent collision belts, examples being the Early Palaeozoic Scandinavian Caledonides and the thrusts in the Moines of northwest Scotland.

A famous formulation of James Hutton's theory of the Earth was that the ‘present is the key to the past’. This sounds simple and obvious, but it involves huge assumptions about whether processes we see operating now did so in the distant geological past. Were rivers, and the sediment they are carrying into the seas, always there? The Huttonian formulation receives its most severe test when we go back to the Archaean, but even Palaeozoic orogens call for geological detective work on a grand scale. In older orogenies it is as if we are dealing with a manuscript from which most of the pages have been torn. If we apply the Huttonian dictum, we need to ask: what are the keys to present day orogens?

Firstly, there is the ocean crust which is being subducted. From this we have a method of determining the rates of convergence, using the magnetic anomalies. Obviously most or all of this evidence is lost in ancient orogens where it is a case of *habeas oceanus* – produce the ocean! However, there are places where bits of ancient oceanic crust have survived because the crust has not been subducted, but instead obducted onto the continent. Secondly, much of the evidence for continental drift comes from palaeomagnetism, from which it is possible to determine the latitude but not the longitude at which a rock was formed. A sequence of such measurements through time gives us a means of tracking continental drift. This is still possible in ancient orogens unless metamorphism has destroyed the fossil magnetism. Thirdly, within orogens the original order of deposition of strata (that is, oldest at the bottom and the youngest at the top) may become inverted by either recumbent folding or thrusting. In the Alps, stratigraphic inversions were recognised by the nineteenth-century geologists using the fossil content. But the fossil assemblages which make it possible to determine a succession of strata did not exist before about 600 Ma, so this technique cannot be employed in the Precambrian orogens. Long before continental drift was accepted, palaeontologists puzzled over the fact that the Cambrian of Britain showed two distinct trilobite faunas, the Olenellids of NW Scotland and Paradoxides of Wales. The conclusion is that as we go back in time the standard techniques disappear one by one. Of course the lack of a timescale based on fossil assemblages can be countered by use of geochronological dating, but as we go back in time our geological ‘book’ loses more and more of its pages.

Going back further in time, the Grenville Province of NE Canada, which is found to extend southwards through the USA and into Mexico and South America, has been shown by Gower and others to record the accretion of crustal blocks and collision of continents in the late Mesoproterozoic. Even older collisional belts are identified: for example, St-Onge *et al*. (2006) interpreted the Palaeoproterozoic Trans-Hudson belt of Canada as a continent–continent collision zone with many similarities to the Himalaya. These and other examples from around the globe (e.g. the Irumide Belt, Limpopo Belt) provide reasonable grounds to presume that plate tectonics have operated for at least 2.0 Ga. The Hadean and Archaean, from 4.4 to 2.5 Ga, are much more problematic. Since the time of Sederholm (early 20th century), the metamorphic rocks of the Archaean have been regarded mostly as the deeply buried parts of orogenic belts now exposed at the surface as a result of erosion. Since the thickness of Archaean crust is much the same as present day continental crust outside orogens (*c*.35 km), the inference is made that there has been a great loss of cover. This is supported by the estimates of elevated pressures and temperatures identified in exposed rocks of Archaean age. Therefore a process of crustal thickening must be involved in Archaean tectonics, presumably a result of thrust stacking or folding similar to that which can be seen in the Himalaya or the Alps. Friend and Nutman (2005a) and others have argued that this was the case in the late Archaean assembly of the gneiss belts of west Greenland, which have distinct histories prior to their shared deformation events after 2700 Ma. However, the recognition of thrusts and estimation of the amount of lateral movement along them are greatly hampered by the general lack of stratigraphical information, especially way-up criteria, in many Archaean rocks.

Despite these difficulties, the conclusion is that the Dewey and Bird (1970) classification probably applies even in the Archaean, at least that part of it where continents and oceans existed and the plate tectonics model of subducting ocean floor can be applied. If Archaean oceans and ocean crust existed then they have all been eliminated, the only possible traces being the occurrences of Archaean ophiolites now incorporated into continental crust. Plate tectonics is the only process known that can eliminate oceans.

Before taking up specific problems it is useful to give a brief review of the main features of some orogenic belts in order to gain an acquaintance with them. The treatment here is on a large scale, therefore many interesting topics – for instance structural analysis, strain determination, metamorphic studies – are at best mentioned briefly. In the first part of the book, examples are confined to Phanerozoic orogens because, as mentioned above, the younger mountain belts offer a better chance of understanding evolutionary processes in orogenesis than the older deeply eroded belts.

Major features of orogens

Our aim is to examine the factors controlling the morphology and evolution of orogenic belts that are familiar features in the geological record from the Archaean. Characteristically orogenic belts are long linear or curvilinear features, as much as several thousand kilometres long, within which the continental lithosphere has undergone contraction to varying extents. Conspicuous examples are the Alpine–Himalayan belt and the Cordillera on the west coasts of North and South America.

Orogenic deformation

Calculations of orogenic strain by study on a small scale of deformed objects, such as deformed pebbles or fossils, and on a large scale using a procedure called retro-deformation (removal of the deformation structures in order to restore the rocks to their state prior to orogenesis), suggest that contractions vary greatly from belt to belt but can reach the order of 80%, meaning that the rocks in an orogen occupy only a fifth of their original horizontal dimensions.

Mechanisms of lithospheric thickening

The principal mechanisms of thickening are folding and/or thrust faulting. In the latter, thick bodies of rock are transported along a low angle fault, sometimes for distances of several hundred kilometres. The transport direction (or vergence) for thrusts leads us to another useful terminology, foreland and hinterland – the thrust vergence is usually towards the foreland and away from the hinterland of the orogenic belt. In simple terms, the contraction results in a thickened lithosphere and its topographic expression is high mountains.

One of the interesting aspects of orogeny is the mechanism whereby thickened lithosphere returns to normal thickness. The process is termed orogenic collapse and accounts for the well known fact that many older orogens are now at low elevations. However, an understanding of the process is made easier in recent orogens which show a better preserved record of the orogen, especially the early stages of collapse.

Orogenic metamorphism

An extremely important feature of many orogens is the heating of the rocks, commonly producing regional metamorphism, over a range of temperatures from about 300 °C to 750 °C and pressures ranging up to 10–12 kbar, equivalent to a depth of *c*.40 km. The resulting regional metamorphism, known as medium-pressure, medium P/T or 'Barrovian' metamorphism, is, as we shall see, typical of many orogens and as such provides an important constraint on how orogens may evolve and 'work' at depth. However, it is not only the metamorphic signature of orogeny. In many young orogens we also see mineralogical evidence for the burial of oceanic and continental rocks to depths of 100–150 km or more, producing eclogites and ultra-high-pressure rocks that in some instances contain microdiamonds as well as the high-pressure equivalent of quartz, coesite. The Triassic collision belts of China (Dabei Mountains, Shandong) and parts of the Caledonian in Norway provide spectacular examples of the extreme of metamorphism, which has also been identified in the Alps and Himalaya by Chopin (2003), O'Brien (2001) and others.

Orogeny may also produce metamorphic rocks that have experienced remarkably high temperatures of over 900 °C at depths of 20–40 km. These ultra-high-temperature (UHT) granulites are not only found in exhumed ancient belts like the *c*.2600–2500 Ma Archaean Napier Complex of Antarctica, the 100 Ma Eastern Ghats granulites of India and numerous 'pan African' (600–530 Ma) complexes preserved in the southern continents, but are also recognised in young and recent orogens. We can directly study the processes operating in the deeper parts of orogenic belts, where granulites appear to dominate, by looking at old deeply eroded belts such as the Caledonian in Scotland and Norway and the Grenvillian in Canada. However, geophysical techniques nowadays permit insights into the rheology and mode of deformation of the rocks, with an increasing weakening or softening as the temperature rises and metamorphic reactions take place. In addition to this the breakdown of hydrous minerals, through metamorphic reactions that take place as temperatures increase, results in the release of water. This provides another important control on rheology, for example by facilitating grain boundary migration of material or by raising fluid pressures in a column of rock; see Chapter 3.

Further reading

Bailey, E.B. (1935). *Tectonic Essays: Mainly Alpine*. Oxford: Clarendon Press.

Holdsworth, R.E., Buick, I.S. and Hand, M. (eds.) *Continental Reactivation and Reworking*. Geological Society of London, Special Publication, **184**, 57–75.

Le Pichon, X., Francheteau, J. and Bonnin, J. (1973). *Plate Tectonics: Developments in Geotectonics*, **6** Amsterdam, London, New York: Elsevier.

Moores, E.M. and Twiss, R J. (1995). *Tectonics*. New York: W.H. Freeman and Company.

Windley, B.F. (1995). *The Evolving Continents*, 3rd edition. New York: John Wiley and Sons.

Cambridge University Press
978-0-521-76556-5 — Orogenesis
Michael R. W. Johnson, Simon L. Harley
Excerpt
More Information

2 Driving mechanisms for plates, slab retreat and advance, and a cause of orogenesis

In 1928 Arthur Holmes suggested that the mechanism for continental drift is cells of convection in the mantle. This was a remarkable insight, although many would now question the one-to-one connection between plate motion and mantle convection. So what is the modern view on the driving force for plate movements? There are two models in which the plates drive themselves. The first is called ‘slab pull’, which means that the dense ocean crust exerts a pull on the ocean floor during subduction as it plunges into hot asthenosphere. In contrast, the less dense continental crust is relatively buoyant. Sometimes the subducted slab of ocean crust breaks off and sinks into the hot asthenosphere, but if it survives it will exert a traction and in effect pull the ocean crust away from the Mid Ocean Rise. The opposite view is ‘slab push’, which means that the driving force for the moving ocean floor is situated at the Mid Ocean Rise which is opening under extension to allow in the new ocean crust.

Perhaps it should not be either/or here. Phillip England (1982) calculated the required stresses at the Mid Ocean Rise in the Indian Ocean if slab push were to be responsible for the northward movement of the Indian plate carrying the Indian continent. The forces acting on a plate boundary must do work against gravity during the raising of high mountains and plateaux. The force balance must take into account the Argand number, which expresses the relative magnitudes of the buoyancy forces arising from contrasts in crustal thickness and the forces required to deform the medium. England's results show that the horizontal stress arising from slab push is enough to explain not only the motion of the Indian plate before collision but also the continuation of motion after the India–Asia collision, with the result that India indents Asia, and a wave of deformation has spread across the Asian continent for over 2000 km north of the Himalaya. Using a viscous sheet model and a non-Newtonian rheology for the lithosphere, England showed that the elevated Mid Ocean Rises relative to the deep ocean basins provide a force of 2×10^{12} N per metre and the negative buoyancy of the slabs may provide about 2×10^{13} N per metre of trench. The estimated average driving force per unit length of subducting slab is 5×10^{12} N/m, enough to provide a reasonable balance for the forces resisting plate motion. The implication is that the continuing orogeny in southeast Asia requires the driving force given by 2500–5000 km of subducting slab or 12,000 km of Rise. These conditions are met in broad terms in the Indian plate, and so there is plenty of available force (slab push) to drive the Indian plate. The extensive slab system there is crucial in the Indo-Asian collision, in contrast to the smaller slab in the case of the Africa–Europe collision which was marked by slow collision and substantial strike-slip motion.

The above account firmly relates orogenesis to plate convergence, and there is a broad consensus now on that interpretation, but we should mention other models. For example,