CHAPTER 5

Tectonics

Key words: Continental drift, plate tectonics, subduction, obduction, Mid Ocean Ridges, Atlantic Ocean, Mediterranean Sea, continents, folds, faults, earthquakes, volcanoes.

Introduction

At the beginning of the 20th Century the geologist Alfred Wegener proposed the theory of continental drift to explain the dynamics of the Earth's surface, based mainly on an observation of the apparent fit of the coasts of some continents - in particular western Africa and eastern South America. He believed then that continental drift was driven by both external factors (e.g. the rotation of Earth) and internal factors (e.g. geothermal energy).

His theory was highly controversial but after the second World War, the combination of oceanographic (i.e. sea bed structure) and palaeomagnetic and radiometric dating studies of sea floor rocks – as well as studies on palaeogeography and fossils – gave a much more comprehensive evidence for continental drift. This ultimately led to the establishment of plate tectonics as a theoretical framework for Earth Sciences in the late 1960s and early 1970s. A key and influential publication from this time was written by Dewey and Bird and published in 1972 and described the different types of plate movement and collision.

5.1. How the "Theory of Continental Drift" became the "Plate Tectonics"

Alfred Wegener proposed the **theory of continental drift** in 1912 based on a study of continental coastlines and attributed movement of the continents to both external and internal forces acting on the Earth. After many years of discussion, the theory was proven in the late 1960s and early 1970s through studies of palaeomagnetism, radiometric dating, palaeogeography and the distribution of fossil groups (i.e. palaeobiogeography).

Plate Tectonics is the unifying term with which Continental drift and related aspects of the evolution of the Earth's crust are known today, having been confirmed and established as the framework within which many aspects of the Earth Sciences can be placed. It is now known that the surface of the Earth is made up of vast, essentially rigid slabs of crust known as plates, which are always in dynamic movement with respect to each other.

5.2. What is seafloor spreading?

The ocean floor is being continuously renewed by the production of basaltic volcanic rocks along lines known as 'Mid Ocean Ridges'. The main factors responsible for this volcanic activity and the creation of new oceanic crust are:
1) The release of pressure as ocean crust is thinned by stretching at Mid Ocean Ridges, which allows the mantle below to rise and melt, and, more locally.
2) Processes related to the interaction of the lower part of the Earth's mantle and the outer core, which leads to localised heating and melting of the mantle and the rise of molten magma in what are known as *'Mantle plumes'*.
The process of seafloor spreading, which occurs at Mid Ocean Ridges, however, is driven by great convection currents, which develop in the mantle, with hot material rising and colder material sinking. This is the force that pulls the continents apart or pushes them together, making them collide, crumpling them in the process to form mountains such as Himalayas, the Alps or the Pyrenees.
Mid Ocean Ridges begin to form when these convection currents diverge at the surface and pull the crust apart creating 'Constructive Plate Margins', whilst 'Destructive Plate margins' are where plates are moving together, as heavier oceanic crust sinks below lighter continental crust in what are known as 'Subduction Zones'. When all of this oceanic crust has been consumed by subduction continents collide and the great mountain ranges are formed. Due to the broadly spherical shape of the Earth, however, in places these plates are simply sliding past each other in what are known as 'Conservative Plate Margins'.
As a consequence, continents have been changing their position through time and aggregated or disaggregated as convection currents have pulled them apart or made them collide. Similarly, oceans have been opening and closing through time as convection currents have caused Mid Ocean Ridges to develop, creating new ocean crust, or destroying ocean crust in subduction zones, leading to volcanic and tectonic activity – the latter as sinking material is melted to produce magma which rises to the surface. The latter produces volcanic 'Island Arcs', such as in Indonesia, where ocean crust sinks beneath ocean crust, or mountain belts with active volcanoes where oceanic seafloor is subducted below continental crust – which is crumpled in the process – as in the Andes and Rockies of the south and north Americas respectively. The compressed, deformed and uplifted materials are called 'Orogenes' and they form mountain ranges as they rise.

5.3. Geophysical, Geological, Palaeontological and Palaeoclimatic evidence for Continental Drift and Plate Tectonics

Background: Fundamentally, the concept of continental drift and plate tectonics states that the Earth's crust is formed by thick, less dense continental blocks composed of granitic, metamorphic and sedimentary rocks and denser oceanic plates, formed of Fe-Mg-enriched rocks - the latter forming the ocean floor, but also underlying continental crust. Both types of plates move and displace each other as they are pushed together (i.e. accretion) or split apart (i.e. rifting) by forces generated in the upper Mantle (the *Asthenosphere*), by convection currents. The history of planet Earth, therefore, from the moment of the crystallization of a first solid crust, has been on one side a story of the accretion and collision of continental plates and on the other, of generation and destruction of oceanic plates. Displacement of these oceanic plates would push the continental plates and make them collide, but, as oceanic plates are denser, they can also sink below continental plates through the process of *subduction*.

Main evidence: Scientific support for the Plate Tectonics theory has come from geophysical, geological, palaeontological, palaeoclimatic and geodesic studies. This evidence has demonstrated that although many continental masses are now far apart, millions of years ago they were united, forming a single supercontinent known as Pangaea. This supercontinent began to split up over 200 million years ago, forming the separate continents we know today. Evidence of this split and subsequent movement comes from radiometric, palaeomagnetic, palaeontological, petrological and stratigraphical studies.

5.4. About the position of the continents through time

Studies in Geophysics (including palaeomagnetism and radiometric dating), fossils, palaeoclimatic indicators and other geological data have been crucial for demonstrating that the continents have not been in the same position through Earth History. As iron-bearing minerals, such as magnetite, are common in basaltic and other igneous rocks and retain the orientation of the magnetic north pole in the moment of the formation of the rock, geophysicists can reconstruct the former position of a continent or oceanic plate by comparing the present day magnetic orientation of the minerals with their original orientation. In addition, a comparison of stratigraphical successions and fossil assemblages of similar age on different continents can also enable a palaeogeographic reconstruction of the original position, and evolution through time, of each continental block. For this reason, fossils are also essential tools for plate tectonic studies.

It is clear that the continents have been continuously changing their relative positions through time, indeed oceans and continents have been in a permanent state of change and evolution throughout the history of Earth. Aggregation of continental masses from the consolidation of the first crust through the Archaean and Proterozoic eons led to the formation of a first big supercontinent, known as Rodinia, around 700 million years ago. From the early Cambrian Period, around 600 million years ago, this large continent began breaking up into smaller continental masses, the different continental blocks being initially dispersed during the Early Palaeozoic Era. In the later Palaeozoic, however, they were re-aggregated again into a new large continental mass, the supercontinent 'Pangaea'.

From the early Mesozoic Era, from the Triassic Period onwards, Pangaea in turn started disaggregating into smaller continental fragments as new oceans (including the Atlantic, Indian and Tethys oceans) opened. From the Cretaceous, however, the Tethys, which had separated the continents of Laurasia and Gondwana, started closing as the South Atlantic Ocean opened and started pushing the African continent in the opposite direction. The Mediterranean Sea is effectively all that's left of this ocean.

5.5. About plate tectonics and building mountain ranges

Oceans have formed when continents have been pulled apart by the development of a Mid Ocean Ridge, for instance the Mid Atlantic ridge, which extends from the Arctic, through Iceland, to southern latitudes close to Antarctica.

Mountain ranges have formed when continents have collided, or where an oceanic plate has been subducted below a continent. These processes lead to the folding and uplifting the continental margin including the thick sedimentary sequences deposited in the marginal sedimentary basins, leading to the formation of mountain ranges.

5.6. About folds

Folds are the result of the deformation of rocks by a compressive force. They can take place in every sort of rock but they are most likely to be seen in layered rocks, such as sedimentary rocks or some metamorphic rocks.

When sediments are subject to high pressures by the weight of further sediments accumulating above them in sedimentary basins, they undergo *compaction* and become *lithified sedimentary rocks*. When sedimentary rocks are subjected to lateral compression by tectonic forces – typically over a long period of time and in combination with some heating during deep burial - the elastic limit of the rocks can be exceeded and they can become plastically deformed. This is known as ductile deformation. However, many folds develop in rocks which are nearer to the surface and can be more angular due to a more brittle deformation.

Anticlines and synclines are basic fold types and the main structures that can be formed as a result of both brittle and ductile deformation. They are especially visible in sedimentary rocks although they can also develop in metamorphic rocks as they undergo tectonic deformation.

An *anticline* is a fold in which the younger strata are to the outside, whilst the older rocks form the core or the internal part of the fold. Anticlines can be recognized by their typical 'A'-shape.

A *syncline* is an opposite structure, being a fold in which the younger strata form the internal part of the structure whilst the strata to the outside are older. It can be identified by a typical 'V' or 'U'-shape. Where the relative age of the layers within the fold cannot be determined, 'A'-shaped folds are known as *antiforms*, and 'U'-shaped folds are known as *synforms*.

As both anticlines and synclines affect stratified rocks that once were horizontal, they can form a distinctive pattern on a geological map, at varying scales from many kilometres to only a few 10s of metres (any smaller would be difficult to record on a map). The line that follows the *hinge* of the folded beds is the *fold axis*, whilst the geometrical plane that symmetrically dissects, or divides, the folded structure into two, is the *fold plane*. The sides of a fold, in which the beds are inclined in opposite directions, are called the *limbs* of the fold. In a symmetrical fold, the fold plane is vertical, i.e. it forms a 90° angle with the horizontal surface. However, as a result of intense tectonic efforts in one dominant direction, the folds can be pushed beyond the vertical plane and then the fold plane is *inclined* with respect to the orientation the dominant pressure. In such cases the fold plane shows a *vergence* in this direction. The vergence of a fold provides crucial information about the direction of the forces that formed it.

If this compression is particularly strong and continues for a longer period of time, the whole structure can be pushed over to a virtually horizontal position, forming a *recumbent fold*, where one limb now overlies the other. In such cases, the limb that lies below shows an *inverted* stratigraphic sequence, with the younger beds below and the older beds above. Recognising that a stratigraphic sequence is inverted is extremely important for geologists as it indicates that the beds have been intensely folded, and recent erosion has destroyed the upper part of the fold structure, leaving only the lower inverted limb preserved. As compression continues, a fold can even be detached from its base and displaced along a sub-horizontal fracture plane to the point that it can be pushed over more recent, even relatively less-deformed, materials. This process is called *overthrusting*.

Thrusted beds forming sets of folded stratigraphic units, which can be classified as tectonic units are called *thrusts*. These thrusts can be completely detached and displaced from the point where they were formed, even for tens or even hundreds of kilometres. They form *allochthonous* (= transported) tectonic units, known by the Swiss term *Nappe*. Thrusted nappes are common, major tectonic structures in many mountain ranges whereas the consequence of plate collision, they can be displaced for many kilometres in both directions relative to the mean sense of plate movement. This is classically the case of the Alps, where important thrusted units have been detached and displaced in divergent directions to form different marginal (or 'external') mountain ranges such as the Subalpine chains in Provence (France), the French Jura and the Swiss Jura. In the Hellenides, in Greece, the external structures of the Pindos Mountains and many other mountain ranges have been detached and thrusted to the east and southeast for many kilometres, and similar phenomena are also seen in the Betic ranges (S. Spain), Cantabrian mountains (N. Spain) and Pyrenees (NE Spain and SE France).

5.7. About faults

Faults and fractures: When rocks are submitted to forces that exceed the limits of ductile deformation they undergo brittle deformation, i.e. they can break along fracture surfaces known as faults. Different types of folds and faults are some of the most important tectonic structures that can affect all the rocks of the Earth's crust.

'Joints', however, are fractures affecting rocks in which blocks on either side have not been displaced. Joints can be generated by different forces, but most are formed as a consequence of decompression when rocks become exposed at the Earth's surface by erosion. They can also be formed as a result of changes of temperature affecting the rocks in the surface. Such changes, for instance freezing and heating, can make the rocks contract and expand, leading to fracturing. The increase of the volume of water as it freezes to form ice, can be a very important factor in high mountain areas where it contributes to fracturing of the rock as it opens up such joints. Faults, however, are fractures along a plane in which the blocks on both sides do undergo displacement by the effect of extensional, compressive, or laterally opposed forces.

When rocks are affected by extensional forces, they can break to form what are called *normal* or *gravitational* faults. In a normal fault, the displaced block moves down long the fault plane so that the younger beds of the sunken block (or *downthrow side*) appear at the same level as the older beds of the other, relatively uplifted block. At a minor scale, normal faults can undergo displacements of only a few centimetres or metres, but they always reflect a state of extension of the surface rocks. At a major scale, normal faults can affect major units of the Earth's crust, resulting in the active subsidence of sedimentary basins at the margins of continents, as well as the relative uplift of adjacent blocks. The latter structures are known as *Horsts* (i.e. uplifted blocks) and the former, *Grabens* (i.e. sunken blocks).

In some cases, the vertical fault plane can bend at depth becoming horizontal. These extensional curved faults are known as *listric* faults. Sliding along the plane of a listric fault will result in the tilting of the faulted block, leading to inclination and sinking of the strata close to the fault plane (i.e. the proximal area), with a corresponding uplift further away (i.e. in the distal area). Listric faults and tilted blocks can be identified when geologists record different thickness of sediments for the same stratigraphic interval in different locations, with the thicker sequence representing more proximal areas where there has been more subsidence and the thinner more distal areas with less subsidence or even relative uplift. Listric faults are fundamental tectonic elements controlling the shape and the evolution of sedimentary basins throughout Earth history.

A reverse fault is a fracture affecting the rocks of Earth crust in which the displaced block moves upwards along the fault plane, so that the lower, older beds of the uplifted block are pushed and emplaced above the younger beds of the down-thrown block. A reverse fault is formed when rocks are subject to strong lateral compression by tectonic forces. At a small scale a reverse fault can show only a small overlap of the uplifted block over the downthrown *block.* At a larger scale, however, reverse faults can become the sliding surface of overthrusted structures (see above) - and at a much, more extreme scale, large tectonic nappes displace large slices of crust

and folded stratigraphic units on large, low angle reverse fault surfaces.
Other tectonic processes associated with faults: Quite commonly, a sedimentary basin that has been formed by subsidence and filling with sediments along normal or listric faults, can be subsequently subject to lateral compression if the former extensional regime turns into a compressive stage. In such case, the sedimentary rocks can be compressed, pushed and thrusted above the margins of the basin following the same fault planes that are now reversed, acting instead as reverse faults. This process is known as *tectonic inversion*, and is a common process in the evolution of **orogenes** and the formation of mountain ranges. This shows that the displacement of large masses of rocks can follow the same fracture plane in both directions, as they constitute significant *weakness zones* of the crust, when can be reactivated, even in an opposite direction.
Strike-slip faults: Strike-slip faults are formed when two large blocks of Earth crust are pushed horizontally in opposite directions along an essentially vertical plane. Such faults can lead to the displacement of crustal blocks over large distances, generally as a consequence of plate movements. At a smaller scale, however, strike-slip faults can lead to an oblique collision of smaller bocks within a compressive regime. The combination of both types of movements is known as either *trans-tension*, if it results in a stretching movement, or *trans-compression* if it leads to an oblique collision of these blocks.
Transform faults also belong to this category of faults. These are major fracture lines that develop in the ocean floor perpendicular to the Mid Ocean Ridge, along which the ocean floor is slowly spreading. Quite commonly, continental blocks can also be displaced relative to each other for long distances along transform faults, a famous example being the San Andreas Fault on the western coast of North America.

5.8. Why and how Earthquakes occur

Earthquakes occur when masses of land move along a fault plane. This displacement can be caused either by extensional movements, for instance in a sedimentary basin which is slowly sinking or *subsiding*, or by compressive movements, for instance associated with plate collision, or by sliding, movements along active *strike-slip* faults (such as the San Andreas).
Although earthquakes can be of very different degrees and magnitude, depending on the displacement of the blocks and the size of the fault itself, they are always connected with tectonic activity, and the abundance and intensity of earthquakes in an area gives a direct expression of the intensity of the tectonic movements in that area.

5.9. How volcanoes are formed

Plate margins are the parts of the lithosphere where geological activity is most intense. This activity can take place in many different ways and one important type is volcanism. Volcanism can take place both at the plate margins or in areas close to destructive margins, as well as associated with other major fractures of the lithosphere.
Volcanic activity takes place when a melted rock (i.e. magma) ascends to the surface. Depending on the different types of rock and the temperature of the magma, there are different types of volcanic activity. Generally, basic lavas (i.e. rich in minerals of Fe and Mg) are more liquid and the eruptions are less violent (e.g. along Mid Ocean Ridges, such as in Iceland or above mantle plumes such as Hawaii), whilst acid lavas (i.e. more rich in silica) are more viscous and eruptions generally more violent and explosive (e.g. above subduction zones, such as in the Andes and

along island arcs such as Indonesia).
The main components of a volcano are: the magma chamber, where the melted rock concentrates, the volcanic vent where the magma ascends to the surface, and the external volcanic crater, where the melted rock is ejected to the surface. A repeated sequence of volcanic eruptions can create a cone of lava and ash around the crater. After many years of successive eruptions, some volcanic cones can reach several thousand of metres in height, as it is the case with Teide, Vesuvius and Etna.

5.10. Why the distance between Europe and North America is increasing?

North America and Europe are getting progressively further apart as the Atlantic Ocean, which separates them, is slowly enlarging.
At the end of the Permian Period, around 250 million years ago, all continents of the planet were united together to form the supercontinent Pangaea. However, this continental mass began to break up through a process of *rifting* and oceanic crust started developing between each section of continental crust, pulling them apart. Firstly, a northern block (Laurentia), which would become N America, separated from another large block (Eurasia), which would eventually become the present day Eurasian continent, and both masses separated from a southern continent (Gondwana), which originally included, South America, Africa, Australia, India and Antarctica.
Through this process, both the northern and the central Atlantic oceans were formed. Subsequently, from the Late Jurassic (around 145 million years ago) and during Cretaceous times, the progress of rifting led to the large continent of Gondwana fragmenting into smaller blocks and what is now South America, Africa and Antarctica started being pulled apart. As the oceanic plates created between them are still pushing the continents away, North America and Europe continue to move further apart, and similarly are South American and African continents.

5.11. Why is the Mediterranean Sea is slowly closing? Will it eventually disappear?

The Mediterranean Sea is all that remains of the once great Tethys Ocean, which separated the Eurasian continent from the continent of Gondwana from the beginning of Mesozoic Era (i.e. Early Triassic times, some 250 million years ago) the Tethys ocean started opening at the end of Paleozoic Era in the Late Permian Period by a series of lines of rifting, which established an area of oceanic crust between the continents, pushing Eurasia and Gondwana apart. As Tethys developed, its margins developed extensive carbonate platform margins, sections of which are now preserved across southern Europe, from Iberia, across France and Italy to Austria and beyond.
From Cretaceous times onwards, however, as the South Atlantic Ocean started to open, the African continent moved slowly in an opposite sense (i.e. counter-clockwise) and started closing the Tethyan Ocean. During the Cenozoic Era, as the African continent approached Eurasia, the sedimentary sequences accumulated along both continental margins were strongly folded and pushed over the continental margins. This continental collision gave rise to the Alpine Orogeny.
In some areas, however, the force of this collision led to slices of the oceanic plate being pushed up onto the continents through a process known as *Obduction*. These slices are preserved in the Alps, in Greece (in the so-called *Hellenic Arches*), in the Betic Cordillera (S. Spain) and in Cyprus (the Troodos Massif).

Today, the Mediterranean Sea is just a small remnant of what the Tethyan Ocean used to be, but it still retains areas of true oceanic sea floor on its bed. The constant rate at which the African plate continues to move towards Europe, (several centimeters every 100 years), however, indicates that the Alpine Orogeny is far from over - indeed, in the next 50 to 100 million years the African Plate will eventually entirely close the Mediterranean Sea and collide against Europe.

Intended learning outcomes:

- Describe briefly the theory of plate tectonics and recognise its importance for the Earth sciences.
- Know about seafloor spreading.
- Know that the continents have changed their relative positions through geological time.
- Understand the relationship between mountain building and plate tectonics.
- Describe the building of mountain ranges.
- Refer to the main types of tectonic structures (e.g. folds, faults etc.).
- Know why and how earthquakes and volcanoes occur and the connection between them.
- Realise the consequences of seafloor spreading, mentioning specific examples.
- Know that plate margins are the parts of the Earth's crust where geological activity is most intense.

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