Chapter 3

Understanding the 'big ideas': major concepts that underpin our current understanding of the Earth

3.1 The rock cycle (Hutton, 18th Century)

James Hutton had the 'big idea' that great cycles of rock formation and deformation had affected the Earth in the past. So in 1788, to show why he believed this, he took his friend John Playfair to Siccar Point on the sea shore near Edinburgh. Playfair saw, exposed on the shore, sedimentary rocks that must have first been laid flat on the bottom of the sea, that were now tilted upwards. Beneath these dipping sediments were even more ancient sediments, dipping more steeply in what we now call an angular unconformity. When James Hutton explained how much time this must have taken, for sediment to be deposited, formed into rock, tilted, eroded and then for more sediment to be deposited on top and the same things to happen, Playfair wrote, 'What clearer evidence could we have had of the different formation of these rocks, and of the long interval which separated their formation ...?'. 'The mind seemed to grow giddy by looking so far into the abyss [great depths] of time.'

Figure 3.1: The unconformity at Siccar Point near Edinburgh. Ancient tilted sediments on top of even more ancient tilted sediments, while modern sediments are being deposited in the sea behind.

At that time, people had no idea of the age of the Earth. Although some scientists had

found evidence that the Earth was ancient, the general public thought that the Earth had formed only around 6000 years ago. So the idea that there had been several cycles in the formation of the Earth and that these had taken a huge amount of time, were revolutionary. If people were to believe these new scientific ideas, then Hutton knew that he would have to find lots of evidence for them.

As Hutton travelled around Scotland and England, he made a range of key scientific observations. He realised that soil was formed by the weathering and erosion of rocks, but that this soil was often then eroded and carried to the sea. In the sea, sediment was deposited and hardened and later uplifted. Hutton knew that sediment was deposited, hardened and uplifted for two reasons. First he had seen the evidence for himself, at Siccar Point and other places. Secondly he realised that this must be happening, since weathering and erosion were continually wearing away the land. If this continued for many years, eventually all land would be eroded to sea level and there would be no land left, unless there was a natural mechanism for uplifting newly-formed sediments again.

So Hutton went searching for a mechanism that could uplift rock sequences. He knew that things expand when heated, and thought this must be the mechanism causing the uplift. We now know that the main cause of uplift is plate tectonics, but this didn't become clear until the 1960s. Nevertheless, Hutton went seeking evidence that the Earth had been greatly heated in the past. He found this in igneous intrusions, by showing that the igneous rocks had been so hot in the past that they had melted and intruded the rocks above. Meanwhile, he found other places where limestone had become so heated that it had changed into marble.

Together, Hutton had discovered scientific evidence for nearly all the processes that we now call the **rock cycle**. He had linked them together into a cycle, and he had realised that there must have been a lot of time available for the processes to produce rocks. We can summarise his discoveries as:

- Weathering - he saw how this attacked 'rocks at the Earth's surface', making 'rotten rocks and soil';

- Erosion/transportation - he knew how soil was eroded into 'mobile sediments';

- Deposition - he saw how sediment was deposited and realised that there must be lots of deposition in the sea, producing 'sedimentary sequences';

- Compaction/cementation - he realised that sediment must naturally become consolidated at the bottom of the sea to form 'sedimentary rocks';

- Metamorphism - he understood that limestone was changed into marble by heat in metamorphism, so marble is a 'metamorphic rock';

- Melting - he had found evidence which showed that igneous rocks had once been hot enough to become molten 'magma';

- Crystallisation - he had found examples of where magma has crystallised into 'igneous rocks';
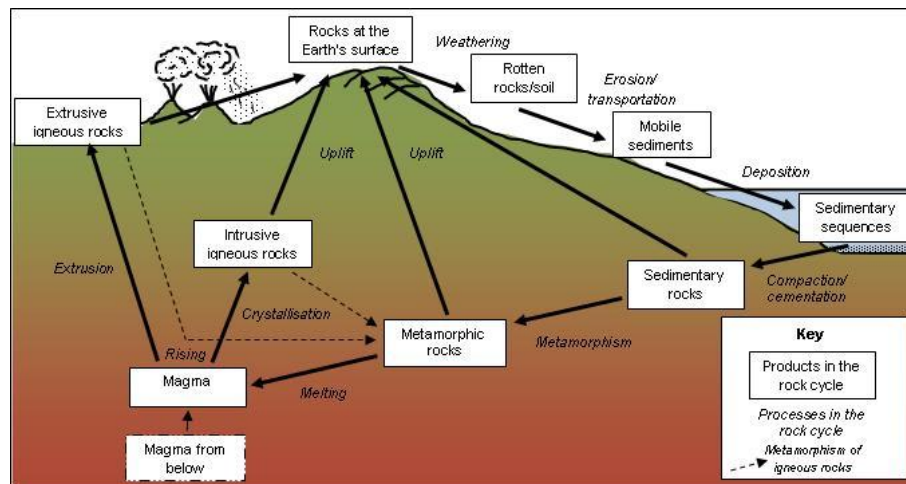
Figure 3.2: The rock cycle, as we know it today.

- Uplift - he had seen many examples where sedimentary, metamorphic and igneous rocks had been uplifted to form new land, exposing new 'rocks at the Earth's surface'.

These are shown on the rock cycle diagram, as we know it today, in Figure 3.2.

But Hutton did even more than work out most of the rock cycle processes. He also realised that rock formation can be explained by the processes that we see working on Earth today. He discovered what was later called the 'Principle of Uniformitarianism' or 'the present is the key to the past'. He worked out that in the past, the Earth must have been subjected to extremely high pressures, enough to uplift and tilt rocks, and very high temperatures, enough to melt rocks. His evidence also showed that the Earth must be very much older than most people thought. He wrote, '... we find no vestige of a beginning, - no prospect of an end', meaning that there was no evidence preserved of how the Earth began, but it must have been an awfully long time ago. There was no evidence of how the world would end either - it would go on and on into the distant future. So we can add to Hutton's roll of geological fame:

- the ideas behind 'the Principle of Uniformitarianism';

- ideas of the enormous pressures and temperatures that had affected the Earth in the past;

- realisation of the great age of the Earth, now called '**geological time**' or '**deep time**'.

Hutton published all his ideas in a book called 'Theory of the Earth' in 1788, but although his friends realised he was a great scientist, his genius as the 'Founder of Modern Geology' was not recognised until many years later. Since then, his work has inspired generations of geologists, including Charles Darwin.

Figure 3.3: James Hutton, the 'Founder of Modern Geology'.

Although geologists through the 1800s and early 1900s knew that the Earth had been subjected to great deformational processes in the past, and knew about the high temperatures of magmas and metamorphic rocks, they didn't know what had caused these enormous pressures and temperatures. Lots of different ideas were suggested, but none of them seemed to give an answer that could explain geological events and their effects across the Earth. One idea put forward in the early 1900s by Alfred Wegener was the 'Theory of continental drift', and this is his story and the story of what followed.

3.2 Plate tectonics (20th Century)

Alfred Wegener lived in Germany in the early 1900s at a time when most geologists believed that the Earth's crust was able to move up and down, but wasn't able to move sideways. Wegener proposed in his '**Theory of continental drift**' that the continents drifted across the Earth's surface, forming mountain chains in mountain-building episodes. Wegener proposed his 'big idea' in 1912 and published the evidence for his idea in a series of books until 1929. Meanwhile, as a polar explorer, he was leading expeditions to Greenland and he died on the Greenland icecap in 1930 when he was 50 years old. Although he found a wide range of evidence to support his theory, his genius wasn't recognised in his lifetime. It wasn't until many years later that geologists realised that many of his ideas did explain a lot of the evidence.

Figure 3.4: Alfred Wegener, the polar explorer and meteorologist who proposed the 'Theory of Continental Drift', as commemorated in this German postage stamp.

The evidence that Wegener used to support his theory included:

- the shapes of the coastlines of South America and Africa showed a very close match - just like a jigsaw puzzle;

- the geology of the two continents, if they were put together, also matched - like a picture on a jigsaw puzzle;

- fossils of land-living organisms found in South America and Africa are very similar and it was very unlikely that they could have evolved separately;

- some modern organisms living in North America and Europe, including a species of earthworm and another of heather, seemed to be identical; it was also unlikely that these had evolved separately;

- countries now found near the Equator have evidence in the rock record that they were covered by ice sheets in the past;

- countries in northern Europe and America that have rock-record evidence of past desert and tropical swamp conditions;

- although some geologists said that the similar fossil species and seemingly identical modern species could be explained by 'land bridges' between today's continents (continents that have now sunk to the ocean floor), geophysical evidence showed that continents couldn't sink;

Upper Carboniferous
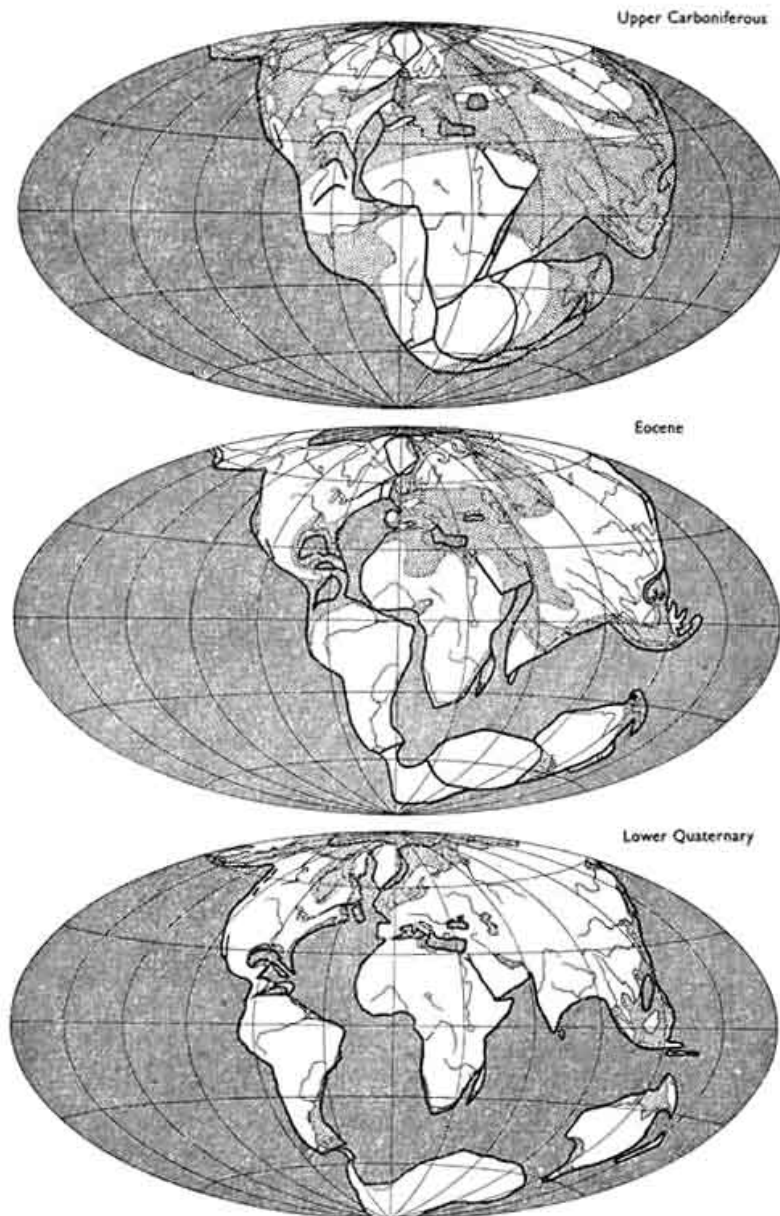
Eocene

Lower Quaternary

FIG. 4. Reconstruction of the map of the world according to drift theory for three epochs.

Hatching denotes oceans, dotted areas are shallow seas; present-day outlines and rivers are given simply to aid identification. The map grid is arbitrary (present-day Africa as reference area; see Chapter 8).

Figure 3.5: A page of Wegener's 1929 book 'The origin of continents and oceans' showing maps of how the continents had moved by his 'Theory of Continental Drift'.

- the longitude of Greenland had been measured in 1820 and 1870 and Wegener measured it again on his 1906/1908 expedition; this showed that Greenland was moving; however, these measurements were later shown to be wrong.

With all this excellent evidence, it is difficult to see why Wegener's 'continental drift' theory was not believed. Some scientists argued that the Earth's crust was not strong enough to form slabs that could be moved across the Earth, whilst others said that there was no force strong enough to make the continents plough through the ocean floors, as Wegener thought. Meanwhile, others argued that the geological features of the Earth could be formed by up and down movements alone. Other factors may have been that Wegener was German, when Germany had just been involved in the First World War, he was a meteorologist by training, and he first published all his work in German. As a result, Wegener's work was disregarded at the time, and Wegener was forgotten.

War played an important part in the next part of the story too, since sonar developed during the Second World War for detecting submarines using sound waves, was used in the 1950s to map the floors of the oceans. This showed that the ocean floors were not flat, but had long mountain ranges, called **oceanic ridges**, and deep **trenches**. Meanwhile, magnetometers that had been developed to detect the magnetism of submarines also showed strange features, when used to map the ocean floors.

Figure 3.6: A ship used for ocean surveying in the 1960s, mapping the sea floor and measuring ocean-floor magnetism.

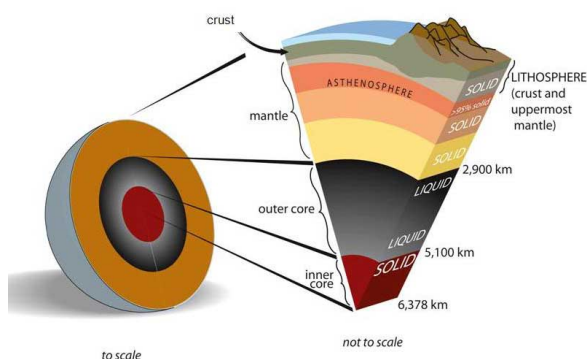In 1962, Harry Hess, an American geologist, published a paper suggesting that the ocean rocks were not ancient, as most people had thought beforehand, but they were geologically young. He proposed that new ocean floor was formed at oceanic ridges near the centres of oceans, and was carried sideways away from these ridges until it sank into oceanic trenches. This was his '**Sea Floor Spreading**' theory, but Hess was able to publish no strong evidence to support his theory, apart from the shapes of the ocean floors. It was a year later, in 1963, that two British geologists, Fred Vine and Drummond Matthews, published their work on the magnetic features they had mapped on ocean floors. It was already known that the Earth's magnetism had 'flipped' many times in the past, with the current magnetic south pole becoming the magnetic north pole, and *vice versa*. The data that Vine and Matthews had collected showed that there were stripes or bands of magnetism running parallel to the oceanic ridges. Some were wide and some were narrow, but the pattern of the stripes was the same on either side of the ridges. This could be explained if the new ocean floor made at the ridges became magnetised as it was formed. The rocks of the ocean floor

Figure 3.7: The structure of the Earth, showing the lithosphere and asthenosphere (not to scale).
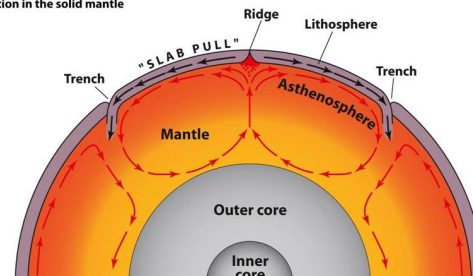
Figure 3.8: Convection currents in the mantle.

therefore recorded the magnetism of the Earth at the time and held this record as the ocean floor was moved sideways, producing the series of stripes they had detected. This was excellent evidence to support Hess's 'Sea Floor Spreading' theory.

It was later in the 1960s that the Canadian geologist, John Tuzo Wilson, put together his work on volcanic hotspots with that of Wegener, Hess, Vine and Matthews and others to suggest that the whole Earth was covered by a series of slabs of rock that moved sideways. His ideas were later called plate tectonics, the slabs of rock are **plates** and their movement is tectonics. He realised that plate margins are found not only at ridges and trenches, but also where there are long faults in the Earth, like the San Andreas Fault in the USA. These large faults at plate boundaries he called **transform faults**.

The new '**Theory of Plate Tectonics**' included Hess's 'Sea Floor Spreading' theory as well as much of Wegener's 'Continental Drift' theory. It showed that continents didn't plough through oceans, as Wegener had thought, but were carried on plates over the Earth's surface. It also provided the mechanism for sideways movement that Wegener couldn't find, since the plates were carried by currents in the mantle beneath them.

It took a few years for geologists across the world to change their ideas, but by the mid-1970s most geologists believed the new theory. Soon, the theory that the whole surface of the Earth had been in sideways motion for millions of years, was being used to explain many puzzling geological features. Like Hutton's 'Principle of Uniformitarianism' and rock cycle ideas before it, plate tectonics revolutionised the thinking of geologists, and provided great insights into Earth processes that are still being used today.

Since the 1970s geologists have continued to investigate the details of plate tectonics and we now have a much better idea of how the plate tectonics machine works, creating new plate material in some parts of the Earth, and destroying it elsewhere, whilst plates slide past each other in other areas. The plates are about 100km thick and are composed of the **crust** and the upper part of the **mantle**, together called the **lithosphere** ('litho' is Greek for 'stone' and it is a sphere because it forms the outer part of the Earth). The lithosphere
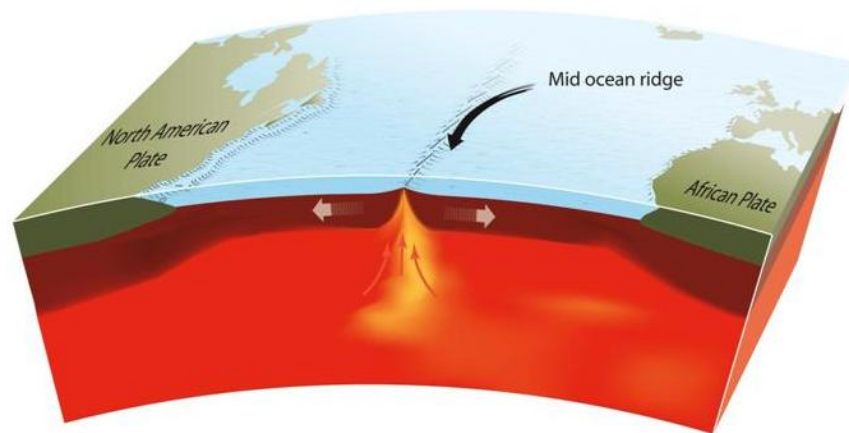
Figure 3.9: The Mid-Atlantic Ridge.

is solid and rigid and so transmits all forms of earthquake waves. Beneath the lithosphere is a narrow zone of the mantle called the **asthenosphere** ('astheno' is Greek for 'weak') which is about 150km thick. We know about the asthenosphere because earthquake waves slow down there. It is so hot that it has begun to melt, containing between 1 and 5% molten rock as coatings around the solid crystals. This means it is able to flow very slowly, about as fast as your fingernails grow. Beneath that is the rest of the mantle, which is solid until it reaches the outer core, at a depth of around 3000km. Because of the enormous temperatures and pressures there, this deep mantle also able to flow, even though it is completely solid.

Where the mantle is particularly hot, the rock there has lower density than the surrounding rock and rises. As it reaches the underside of the lithosphere, it flows out sideways and cools. Eventually, it becomes cool enough to sink again. Currents driven by heat and density differences like this are called **convection currents**, and it is the convection currents in the largely solid mantle that carry the plates of lithosphere across the Earth's surface.

Where convection currents in the mantle rise, the plates of lithosphere above are carried apart. If this happens beneath oceans, this is where Hess's 'sea floor spreading' occurs. New material is added to the plate and as the newly-formed lithosphere is so warm, it swells up to form an oceanic ridge. Oceanic ridges are the longest, widest and highest (from bottom to top) mountain ranges on Earth and link together to form an interconnected chain beneath all oceans. In the centres of the ridges, the movement apart of the plates causes tension. This results in normal faults that move through small earthquakes, causing the central piece of newly-formed lithosphere to slide down in a long narrow **rift valley** at the centre of the ridge. You could visit this rift valley yourself, since the Mid-Atlantic Ridge is above sea level on Iceland, and the rift valley there is a tourist attraction.
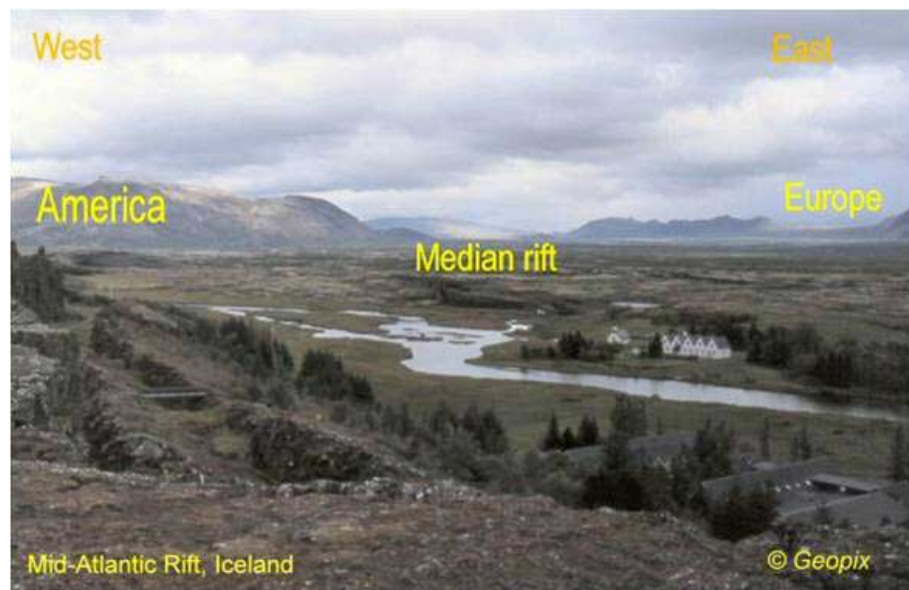
Figure 3.10: The rift valley in the centre of the Mid-Atlantic Ridge on Iceland.

In the centre of the rift valley, on the ocean floor, new plate material is made. The ultramafic mantle material beneath has partially melted to form a mafic melt. This rises and some cools down slowly below the surface to form coarse-grained gabbro. Some rises through fractures as sheets of magma that cool more quickly to form dykes of medium-grained mafic rock called **dolerite**. Some reaches the surface of the sea floor, and erupts as basalt pillow lavas. The newly formed oceanic plate is moved sideways over time whilst sea floor sediments settle onto the surface. This means that the new oceanic crust that forms the top part of the new oceanic lithosphere, has four layers. Three of the layers are of mafic rock, coarse-grained gabbro, with medium-grained dolerite dykes above and pillow basalt flows above that. The top layer is fine-grained deep sea sediment. The rock is new oceanic plate material and so the margin is called a '**constructive plate margin**'. The newly-formed plates are carried sideways, allowing more new plate material to form in the centre, and giving these margins another name, '**divergent plate margins**'.

Iceland is one place on Earth where oceanic plates are growing as new plate material is formed. In Figure 3.10 we can see the central rift valley, where fissures opoen from from time to time, to erupt mafic basalt lava. This runny lava flows quickly and for long distances and can build up over time into great thicknesses of individual lava sheets. These sheets give parts of Iceland a stepped plateau surface, as the flat-lying sheets become eroded back at different rates.

We can map this production line of new plate material through the '**magnetic stripes**'. Mafic rocks contain magnetic minerals that record the direction of the Earth's magnetic field when the minerals crystallised. As the **Earth's magnetic field** has 'flipped' in the geological past, there were times of '**normal' magnetism**, when the magnetic field was the same as it is today, and '**reversed' magnetism'** when the Earth's south magnetic
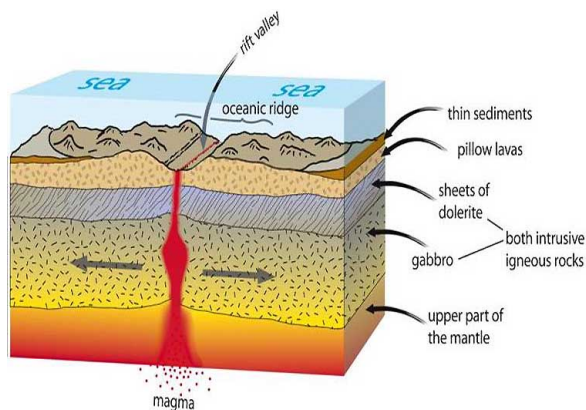
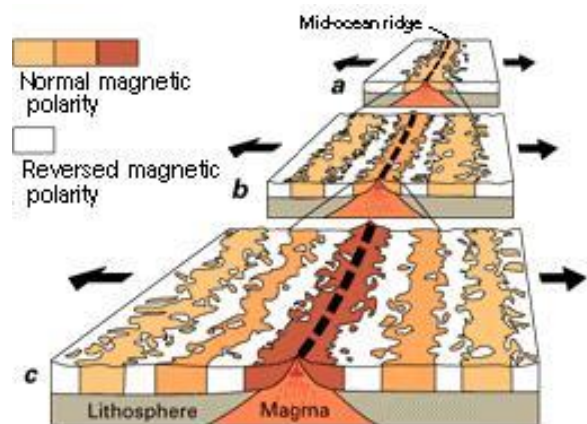Figure 3.11: A constructive boundary, where new oceanic plate is being formed.

Figure 3.12: The formation of magnetic stripes at a constructive plate margin.

pole is where the north magnetic pole is today. If the magnetic field was in the same direction for a long time, a broad stripe of ocean floor formed before it 'flipped' again. But if it changed quickly, only a narrow stripe was formed. Since the same thing happened on both sides of the ridge, the pattern on either side is the same, but reversed. So one side is a mirror image of the other. The 'magnetic stripes' do not form straight lines, since the magnetism is recorded in the igneous rocks, and particularly the basalt lava flows at the surface. How the stripes form, with irregular borders, is shown in Figures 3.12 and 3.13.

The oceanic ridges and the pattern of their magnetic stripes show many places where both ridges and stripes are offset. These are the transform faults, first recognised by J. Tuzo Wilson (see Figure 3.14). These are very unusual faults since, between the two offset ridges, the plates are moving in opposite directions, but beyond the ridges, the plates are moving in the same direction, sometimes at slightly different rates. So, small earthquakes are common in the sections between the ridges, but can also occur beyond the ridges too. One of the longest transform faults, joining two oceanic ridges that are now far apart, is the San Andreas Fault, which runs through California in the USA (see Figure 3.15). As the plate on the western side is moved north, relative to the south-moving plate on the eastern side, there are frequent small earthquakes. There is also the chance of a very large earthquake, like the one that destroyed most of San Francisco in 1906. Since plate material is neither created nor destroyed at transform faults, but is conserved, these are called '**conservative plate margins**'.

As the plates move away from the oceanic ridges they cool down, causing the oceanic ridge to subside. Meanwhile, the blanket of deep sea sediment deposited on the surface becomes thicker. The further the plate has moved, the older the oldest sediment found on the ocean floor. By drilling into these deep sea sediments, we can recover the fossils they contain and date the rocks. This shows that the further away from a plate margin the ocean floor is, the older it is, providing more evidence for the movement of the plates. So maps of the age of ocean floor sediments, such as Figure 3.16, show how the plates have moved over time, and confirm Harry Hess's idea that the ocean floors are geologically
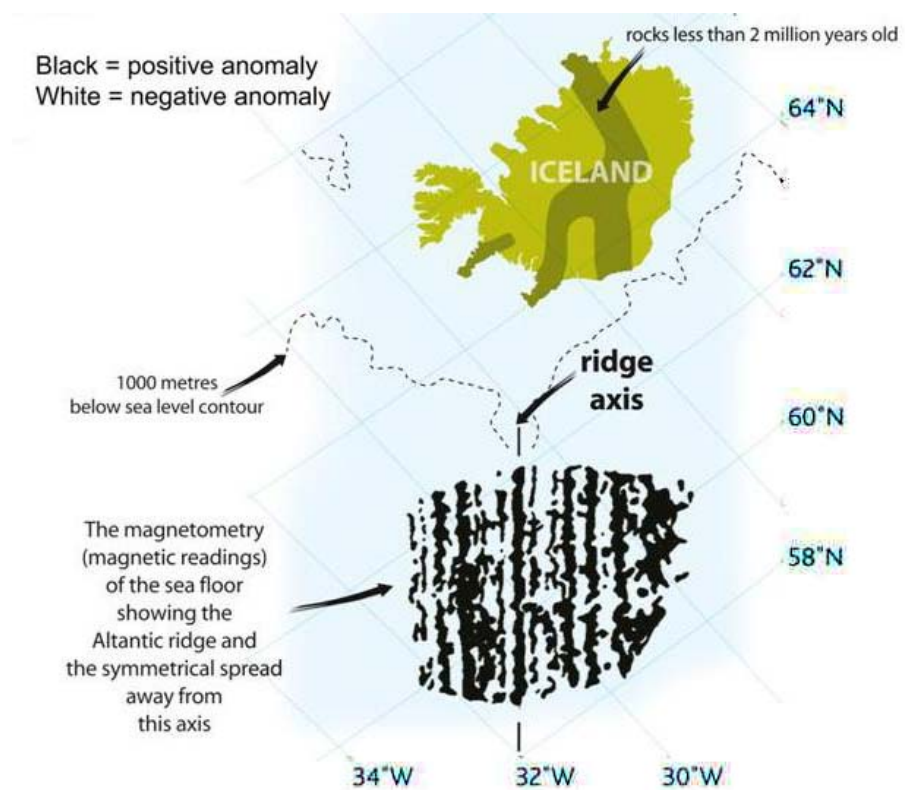
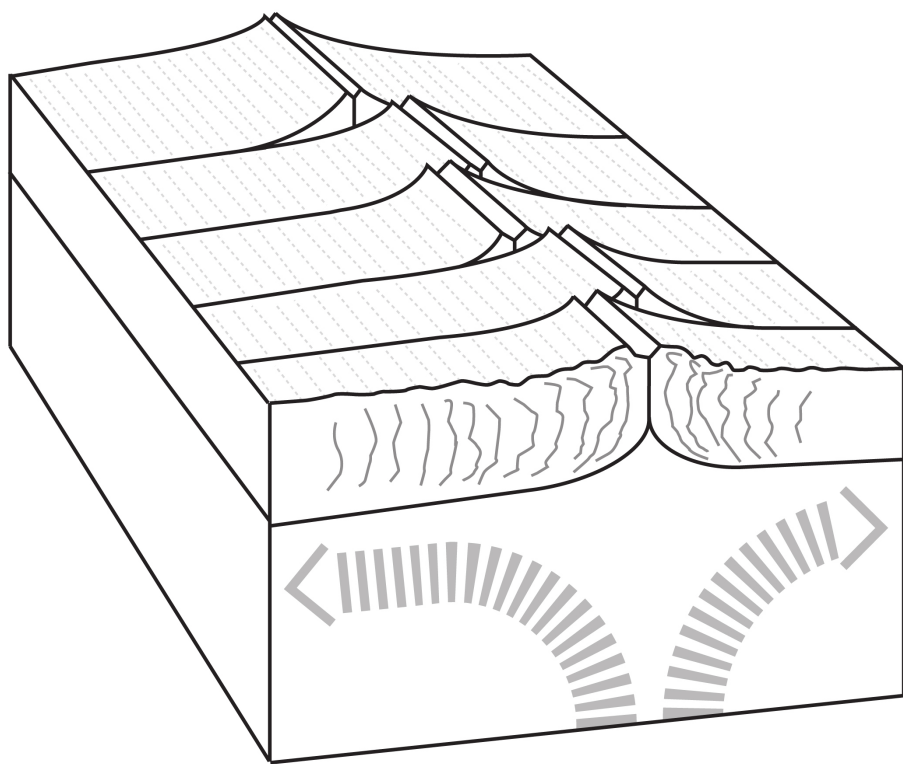Figure 3.13: The magnetic stripes south of Iceland.

Figure 3.14: Oceanic ridges are offset by transform faults.

Figure 3.15: The San Andreas Fault cutting a straight line across California, with a fault scarp on the left and many diverted stream beds.
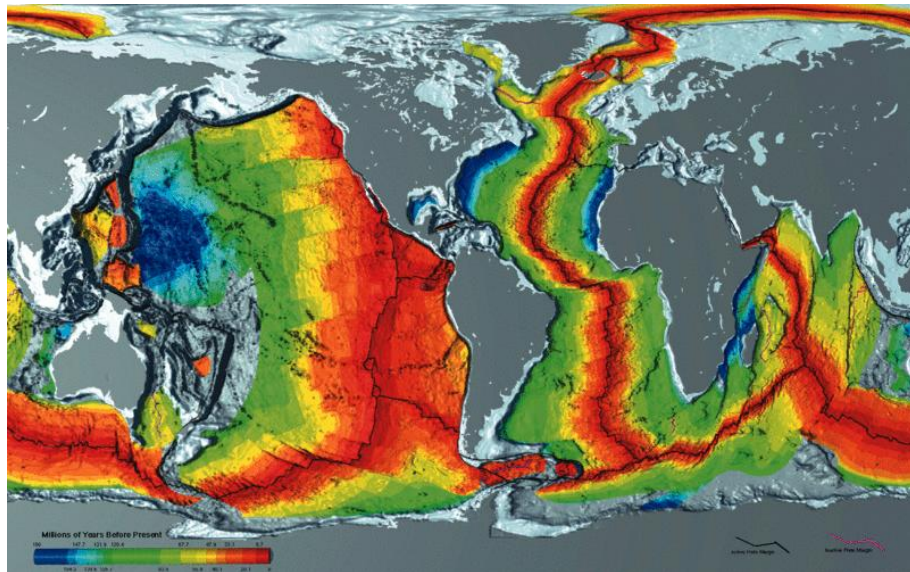
Figure 3.16: The age of the ocean floor, from the youngest in red to the oldest in blue.

young, much younger than many of the rocks that form the continents.

As they are moved across the ocean floors, the plates continue to cool, becoming steadily more dense. Where two oceanic plates meet, the one that has travelled the further will normally be the cooler and the more dense. Since they are moving towards one another, something has to happen, and the denser plate sinks.

The sinking of a dense plate is called **subduction**. We know the angle of plate movement since subduction isn't smooth, but as the plate slides downwards, the friction between the rocks causes it to stick. When the pressure increases, it moves suddenly causing an earthquake. We can plot the positions and depths of these earthquakes and find that they follow a sloping zone into the mantle, called the **Benioff Zone**. As earthquakes occur to a depth of 700km, we know that the lithosphere stays solid and rigid to that depth too. Plates can be subducted into the mantle at different angles, but 45° is common.

The plate of lithosphere which is subducted is made of the upper part of the mantle with mafic igneous crustal rock on top, covered by a blanket of sediment saturated in seawater. As this sinks it becomes heated up and partially melts. The silicon-rich minerals melt first, so that the newly-formed molten rock is richer in silicon, and poorer in iron, than the mafic rock that melts, so the new melt has an intermediate composition. This rises to the surface above the sloping plate and erupts. Since intermediate melts are much thicker than runny basalt melts, they often solidify in the vents of volcanoes resulting in violent eruptions of volcanic ash, associated with slow-flowing andesite lavas. These steep-sided central-vent volcanoes can erupt catastrophically, as in the eruption of Krakatau in 1883, which created tsunamis that killed more than 36,000 people and made the largest sound ever recorded on Earth.

Plates are destroyed at subduction zones, so they are called 'destructive plate margins'.
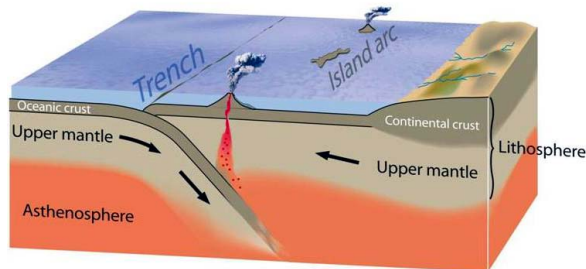
Figure 3.17: An ocean versus ocean destructive margin, with an oceanic trench and an arc of destructive andesitic volcanoes.

Figure 3.18: This volcano in Java shows the typical conical shape of central-vent andesitic volcanoes that form island arcs.

However, the materials the subducted plate is made of are not destroyed but are recycled. The low melting point minerals melt and rise, cooling below the surface or erupting in volcanoes, making new crustal material. The high melting point minerals don't melt, but are taken into the mantle, becoming part of the mantle convection currents.

Destructive plate margins are also called 'convergent margins', since this is where the plates move towards each other. You can see from a world map where on Earth oceanic convergent margins are found, since, when an oceanic plate subducts beneath another oceanic plate, it does so on the curved surface of the Earth and so goes down along a broad curve, which is marked by an oceanic trench (Figure 3.17). A few tens of kilometers away from the trench, above the downward sloping plate, a row of volcanic islands is found (such as that in Figure 3.18). The arc-shape seen on the map of the chain of volcanic islands and the trench is called a volcanic arc. The largest of these, and the one most easily visible on a map, is the Aleutian Island arc in the North Pacific Ocean that links North America to Russia.

When an oceanic plate meets a plate carrying a continent, the continental rocks are much less dense than the oceanic rocks, so it is the oceanic plate that is subducted (Figure 3.19). The subducting plate forms an oceanic trench and causes earthquakes. The plate partially melts here too, forming intermediate magma that rises to form andesitic volcanoes with conical shapes (Figure 3.20).

However, this rising magma also melts the rock at the base of the continental crust. When the continental crust partially melts, it is the low melting point, silicon-rich minerals that melt first, leaving those richer in iron behind. This melt is a silicic melt, even richer in silicon than intermediate magma. If these magmas reach the surface, they are even more viscous than andesitic melts, and produce steep-sided volcanoes with catastrophic eruptions. But most of the magma is so viscous and slow-moving that it never reaches the surface; it cools down slowly below ground in bubble-shaped plutons several kilometers
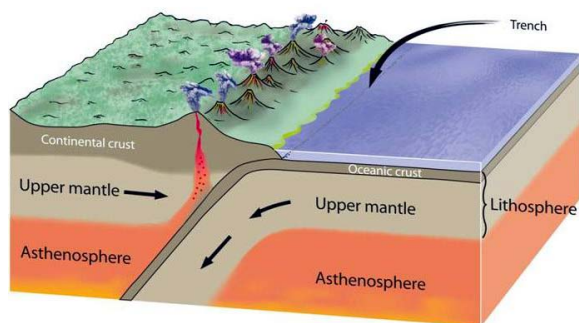
Figure 3.19: An ocean versus continent destructive margin, with an oceanic trench and a mountain range with volcanoes.

Figure 3.20: This volcano in Alaska has the conical shape of most continental volcanoes.

across. These granite plutons form deep in the roots of mountain chains. The mountain chains are produced by compression as the two plates are forced together, causing folding, thrust faulting and regional metamorphism as well as igneous activity.

When two plates meet and both are carrying continents, neither can subduct, since the density of both of them is too low. So the two continental plates are forced together producing enormous compressional forces and creating great mountain chains as the rocks between them are deformed, metamorphosed and intruded by granites (Figure 3.21). The rocks are deformed into tight folds and slabs of crust can be moved many kilometres along thrust faults. The collision of India with Asia in the fairly recent geological past has formed the highest altitude mountain range on Earth, the Himalayas. Since after a time the plates become locked, no further subduction occurs so these great mountain ranges do not have volcanic activity nowadays. But since the plates are still being moved towards one another, major catastrophic earthquakes can occur. In these areas of steep slopes and great erosion, the earthquakes often trigger landslides too, increasing the danger of these active geological regions.

Our modern understanding of plate tectonics has given much more evidence of how it works. J. Tuzo Wilson was able to use his plate tectonic ideas to explain the Hawaiian chain of volcanoes in the Pacific Ocean. The chain trends from south east to north west and only the south eastern-most island still has an active volcano. The islands to the north are extinct volcanoes and there is a continuing chain of extinct volcanoes under water further to the north west. Wilson saw that there must be a rising plume of hot rocks in the mantle beneath, which partially melted to form mafic magmas. These erupted to build up the basaltic volcanoes that form the Hawaiian chain. As the Pacific plate was moved across this plume, older volcanoes became extinct as new ones formed, rather like a piece of paper might burn a line if you moved it across the top of a candle flame. This showed not only how the chain of Hawaiian volcanoes formed, but also the direction of movement and the speed of the plate (Figure 3.22).

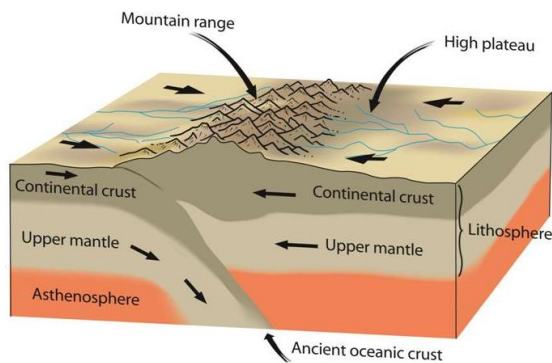Today we have the technology to measure the rate of movement of plates, using such

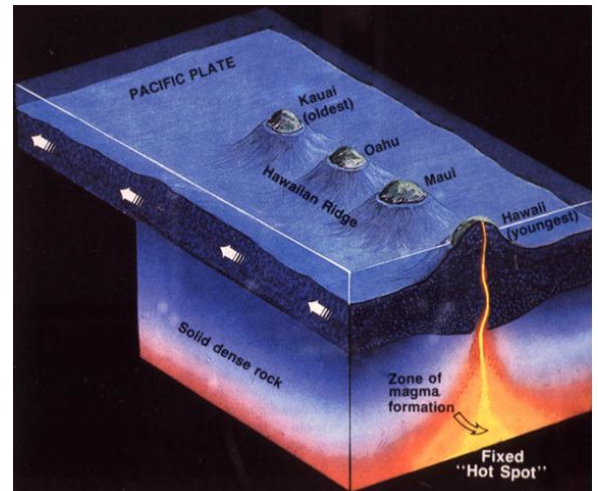Figure 3.21: A continent versus continent destructive margin.

Figure 3.22: The Hawaiian island chain, formed as the Pacific plate was moved across a hot spot in the mantle.
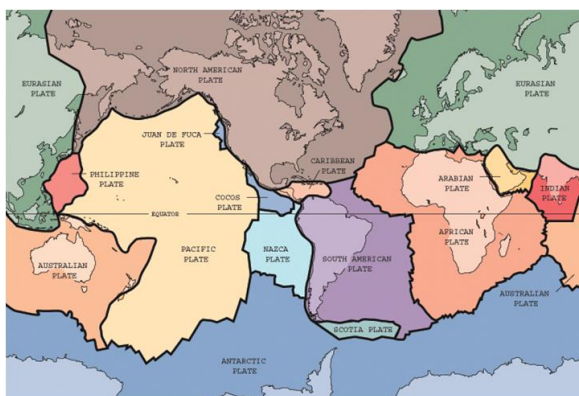

Figure 3.23: Map of the major tectonic plates on Earth.

Figure 3.24: Stromatolite fossils in ancient rocks.

systems as satellite laser ranging and Global Positioning Systems (GPS), used to make regular measurements. These show that plates move from a few millimetres a year to up to 30 millimetres a year. This is about as fast as your fingernails grow.

We have now been able to map the plate boundaries in great detail (Figure 3.23), based on the geographical features found there (oceanic ridges, trenches, island arcs and mountain chains), the tectonic features active there, and the directions of plate movement. Basaltic volcanoes are found at constructive plate margins and at hot spots, andesitic volcanoes at ocean-ocean destructive margins and andesitic and silicic volcanoes at ocean-continent plate margins. Small shallow focus earthquakes occur at constructive plate margins and conservative margins (transform faults) whilst shallow, medium depth and deep earthquakes, that can sometime be large and destructive, are found at destructive plate margins. We can now use maps of the plate boundaries to predict where future tectonic activity is likely, and to understand deep Earth processes across the Earth.

Thus the theory of plate tectonics explains the locations and character of islands and continents, mountain chains and volcanoes, oceanic ridges and trenches. It is the cause of the internal rock cycle processes, like metamorphism and melting, igneous activity and uplift, and it explains why we find desert rocks in tropical regions and tropical rocks in polar regions, as well as the distribution of many species on Earth. Like all good theories, it has provided powerful explanations for many of the Earth's features and processes, but not all. So we need to keep investigating the Earth to find more about how plate tectonics affects our planet and more about the other processes that must be at work when when plate tectonic explanations don't seem to fit.

3.3 Global temperature/sea level change (21st Century)

We know that life has existed on Earth for nearly 3.5 billion years (3.5 thousand, million years), since colonies of stromatolite fossils have been found in rocks that old.

Since life like this can only exist in liquid water, we know that the temperature of Earth for all that time cannot have been below the freezing point of water (0°C) or above the boiling point of water (100°C). Indeed geological research indicates that the mean temperature of the Earth has been between 10°C and 30°C throughout the past 3.5 billion years. This is despite the fact that the Sun has been getting steadily hotter during this time so that the Earth now receives more than 30% more solar energy than it did when it formed. This shows that there must be some natural mechanism or mechanisms that have kept the Earth's temperature between 10° and 30° as the solar energy input has increased. These mechanisms must result in negative feedback.

Feedback affects many different types of systems. When something causes a change in a system, it will have effects. If these effects work against the change, this is called **negative feedback**, whereas if the effects cause the change to increase, it is **positive feedback**. Fortunately for us, the human body has many negative feedback systems. Some of these affect our body temperature; if we get too hot, we sweat and this cools us
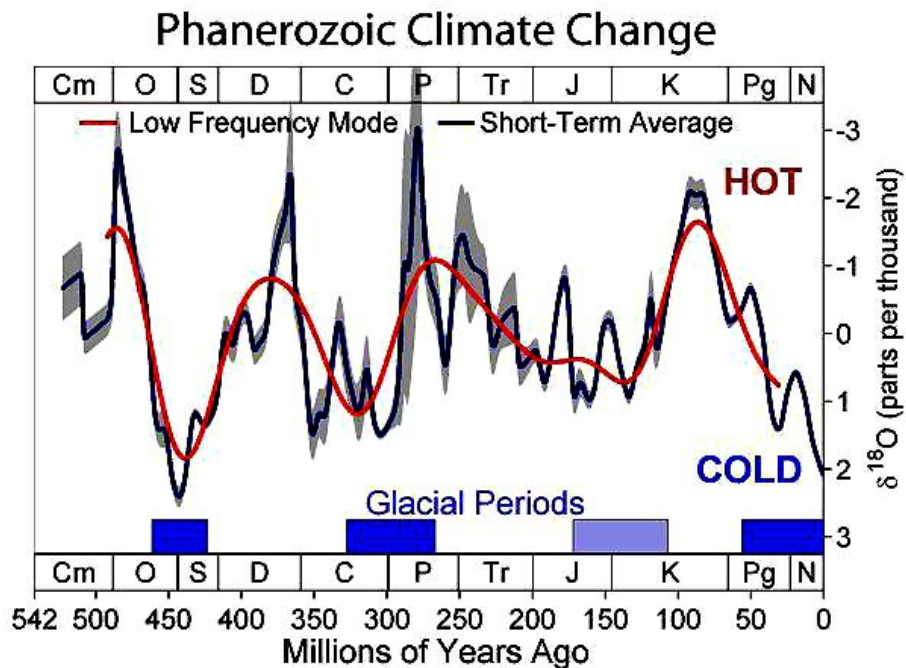
Figure 3.25: Global temperature change over the last 500 million years (the Phanerozioc time period), obtained by measuring change in the oxygen isotope compositions of fossils.

down again. Similarly, if we get too cold, we shiver and this warms us up. These two negative feedback systems stop our body overheating or becoming too cold, and so keep us alive. A human example of positive feedback is a baby breast-feeding; the sucking of the baby causes more milk to be produced so the baby can continue to feed. A second human example occurs when we cut ourselves, the damaged skin releases chemicals that cause the blood to clot and the clotting mechanism releases more chemicals causing more clotting, until the bleeding stops.

The Earth has several feedback mechanisms that affect its temperature and one of these is caused by ice sheets. The white colour of ice sheets reflects sunlight much more than other coloured surfaces; the more light that is reflected, the less there is to warm the Earth. So if the Earth cools, the ice sheets will expand and reflect more light, adding to the cooling of the Earth; a positive feedback effect. Similarly, if the Earth warms, the ice sheets will contract, reflecting less light and adding to the warming effect; positive feedback in the opposite direction.

Another feedback mechanism that affects Earth's temperature involves the amount of carbon dioxide (CO_2) in the atmosphere. Carbon dioxide is one of the so called '**greenhouse gases**' that cause the Earth to be warmer than it otherwise would be the '**greenhouse effect**'. Visible light from the Sun is absorbed by the Earth's surface and some of this is re-radiated as infra-red radiation (heat). All this infra-red radiation would be lost to space if it were not for the greenhouse gases. These absorb some of the outgoing infra-red radiation causing a warming of the atmosphere and of the Earth. If it were not for the
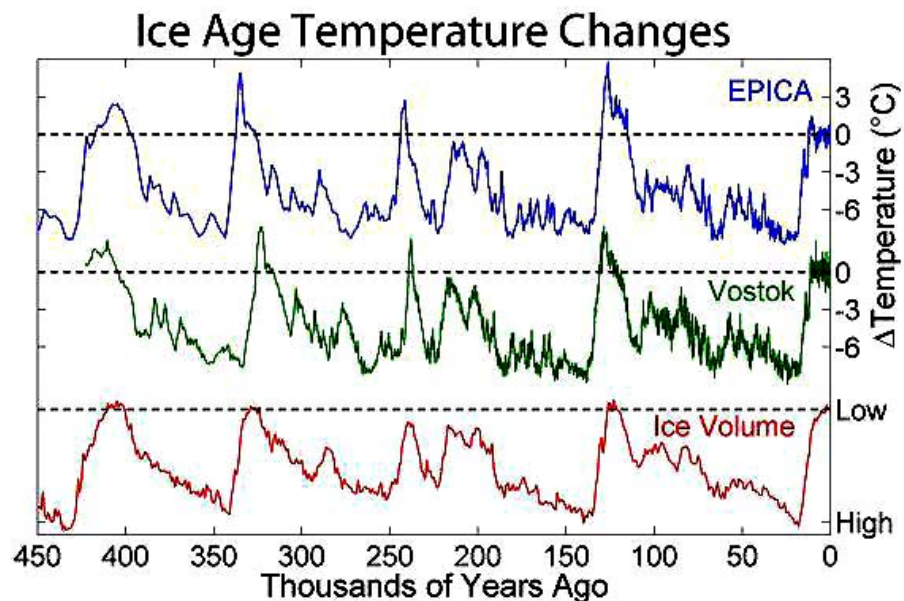
Figure 3.26: Global temperature change over the last 450 thousand years, obtained from duterium isotope measurements. The ratios were measured in the EPICA and Vostock ice cores and have been converted to ice volume estimations in the lower graph.

warming effect of the greenhouse gases, heat from solar radiation would be lost and the Earth would be frozen and could not support life. So the atmosphere has to contain some greenhouse gases for the Earth to be warm enough for life to exist.

Some of the carbon dioxide in the atmosphere dissolves in rain and is carried into the sea. There it is used by organisms to make calcium carbonate shells and reefs. The more carbon dioxide there is in the atmosphere, the more becomes dissolved in the sea and is then available to organisms. So this results in a negative feedback effect; the more carbon dioxide there is in the atmosphere, the more is removed, reducing the amount in the atmosphere.

These are two of the important feedback effects that affect the Earth, but there are many others, some well understood and some not well understood at all. The overall effect of these has been the change of Earth's temperature over geological time, as shown in Figure 3.25. This shows that the Earth has had **glacial periods** in the past, when it was partly covered by ice sheets, and much warmer periods, when there were no ice sheets. As we currently have ice sheets in polar areas, this shows that the Earth is undergoing one of the colder periods of Earth's geological history.

We can obtain information on how Earth's temperature has changed in much more recent geological time by measuring isotope ratios in cores drilled into ice sheets, as shown in Figure 3.26.

This shows that even over the last few hundred thousand years, Earth's temperature has changed greatly, by as much as 10°C between the warmest and coldest periods. It also shows that in geologically recent times, over the last 10,000 years, temperature has re-
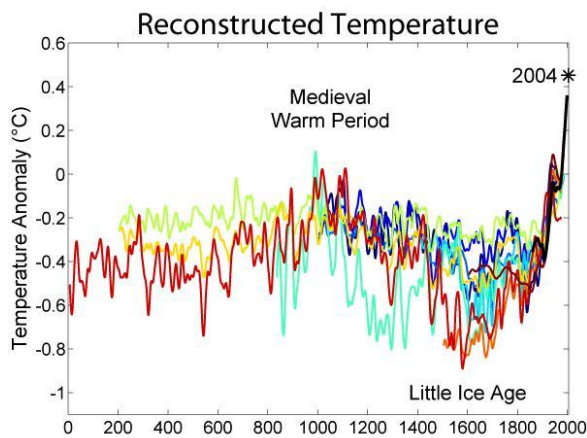
Figure 3.27: Global temperature change over the last 2000 years, compiled from 10 different sources (shown in different colours), including tree ring and glacial data.
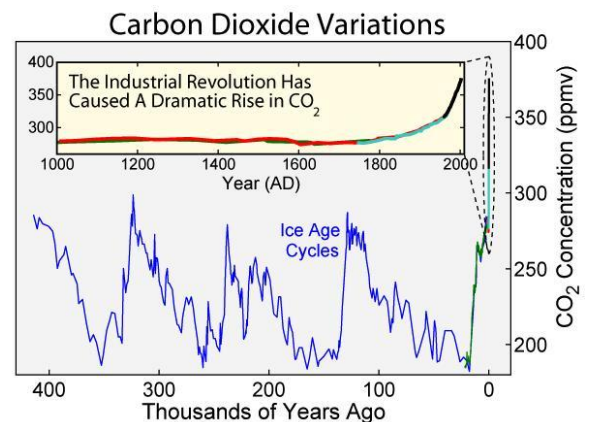
Figure 3.28: The amount of carbon dioxide in the Earth's atmosphere over the past 40,000 years and (inset) the last 1000 years, measured from the bubbles of air trapped in ice cores.

mained particularly stable. This is important is it is the time in which most of human history has taken place; such developments might not have been possible if the temperature had not been so stable.

This is why there is such concern over the recent global warming shown in Figure 3.27. This graph shows that recent temperatures have been 0.3°C warmer than at any time in the last 2000 years and that this temperature increase is increasing.

Temperature increases in the past have been associated with a similar increases in the amount of carbon dioxide in the atmosphere, as shown in Figure 3.28. However, whether the increase is forcing (or causing) the climate change is still being debated.

Nowadays that fact that both Earth's temperature and the carbon dioxide content of the atmosphere have increased over the past 200 years, and are continuing to increase, is not disputed by the majority of scientists. Most scientists also think that the increase in carbon dioxide in the atmosphere is linked to the extensive burning of fossil fuels, like coal and oil, since the industrial revolution began, 200 years ago.

The carbon dioxide in the atmosphere is part of the complex carbon cycle and huge amounts of carbon, cycle through the Earth's systems annually. Plants absorb carbon dioxide and release oxygen during photosynthesis whilst all respiring organisms, plants and animals, have the opposite effect, absorbing oxygen and releasing carbon dioxide. This means that the amount of plant cover on Earth affects the amount of carbon dioxide in the atmosphere, which is why people are concerned about the felling of the tropical rain forests. After deforestation, the Earth's surface can absorb less carbon dioxide, leaving more in the atmosphere.

While most scientists think that the increase of carbon dioxide is the cause of the global warming, some scientists think that global warming is causing the increase of carbon
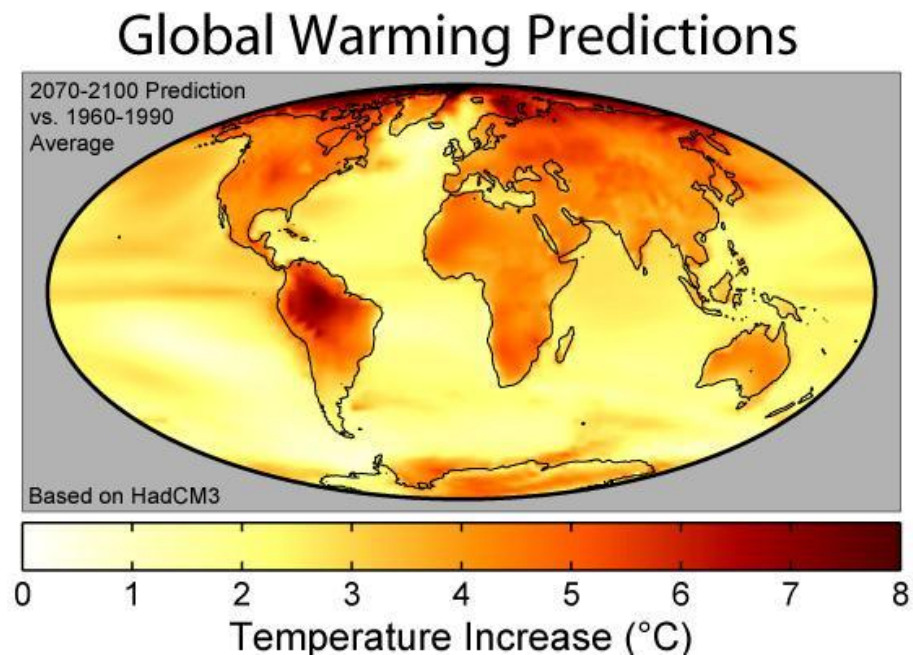
Figure 3.29: A computer generated prediction for the global effects of a 3°C increase in global temperature.

dioxide. This is an area of continuing debate by climate scientists. However, many politicians now believe that impact of the burning of fossil fuels must be reduced, to reduce the amount of greenhouse gases being released into the atmosphere, and so reduce the effects on global warming.

There is still much debate over the effects that global warming might have. Clearly the whole globe would become warmer, but computer-based climate models, based on flows of the ocean and atmosphere (such as in Figure 3.29), suggest that some parts of the Earth would become much hotter whilst others might stay much the same temperature.

Nevertheless, changes like these would have dramatic effects on Earth's climate, with predictions that Earth's weather would become more stormy and that the extent and intensity of drought areas would increase. Such weather changes would affect water and food supplies and so would directly affect humanity.

Such warming would cause ice sheets to melt. If the floating ice sheets on the oceans melted, global sea level would not change, since water from melting ice occupies a smaller volume than the ice itself. However, if the ice sheets on land melted, all the water trapped as ice on the continents above sea level would flow into the sea, causing rises in sea level. Meanwhile, as the ocean waters warm, they expand, further increasing the volume of the oceans. Figure 3.30 shows that if the current trend of continental ice sheet melting and sea level rise continues, sea level is predicted to rise between 20 and 60 cm by 2100.

Many low lying areas of Earth would be very vulnerable to an increase in sea level of half a metre, including most of Earth's major cities, which have been built in coastal areas. If
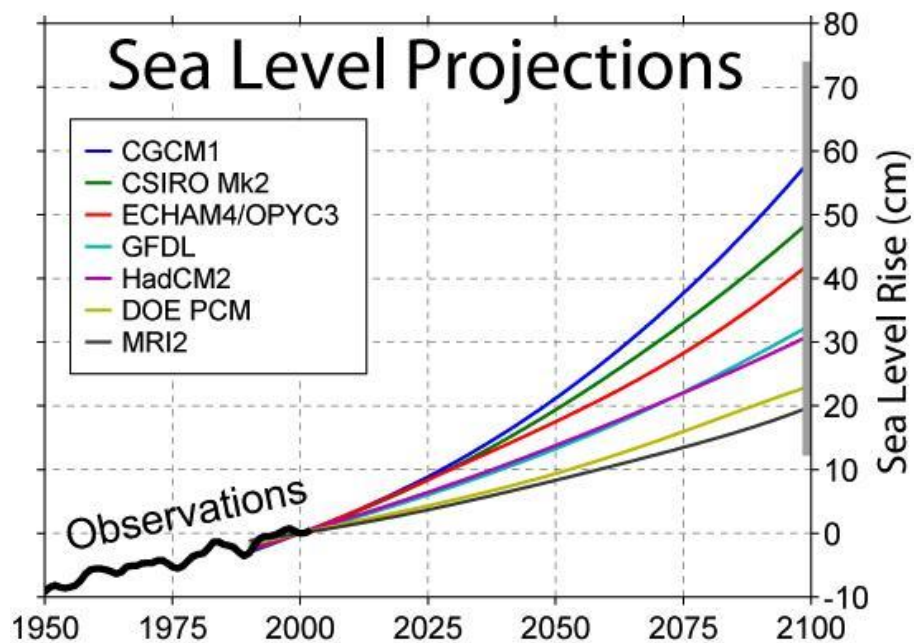
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Figure 3.30: A graph of observed increases in seal level over the past 50 years with projections of the effects of the melting of continental ice sheets in the next 100 years.

sea level continued to rise, the impacts would be even greater.

The geological record contains evidence of sea level change in the recent geological past. During the glacial periods shown in Figure 3.26, such as the one 20,000 years ago, more of the Earth's water was locked up as ice on land than now, so sea level was lower and areas now under water were once land. Thus at low tide in some coastal areas we can find tree stumps of ancient submerged woodland, and these are sometimes found with the artifacts of the humans that lived in the area at the time. Meanwhile, river valley systems cut when sea level was lower, were flooded as sea level rose forming 'drowned valleys', or estuaries on which many of today's ports are based. It is thought that some important human migrations took place during times of lower sea level, such as the native American migration from eastern Asia into North America through the area that is now Alaska and the migration of people into the British Isles, before they became islands.

During periods between the glaciations, also shown on Figure 3.26 (eg. 120,000 years ago), less ice was locked up in continental ice sheets and so sea levels were higher. In coastal areas, beaches were formed at higher levels than today and have now been left as '**raised beaches**' several metres above today's sea level, often with 'fossil cliffs' behind them.

One of the founders of the science of climate change was Charles Keeling who, in 1958, first started to measure the amount of carbon dioxide in the atmosphere accurately. He built a high-precision measuring instrument and sited it on top of a volcanic peak in Hawaii, to be as far away from and as high above human polluting activities as possible.
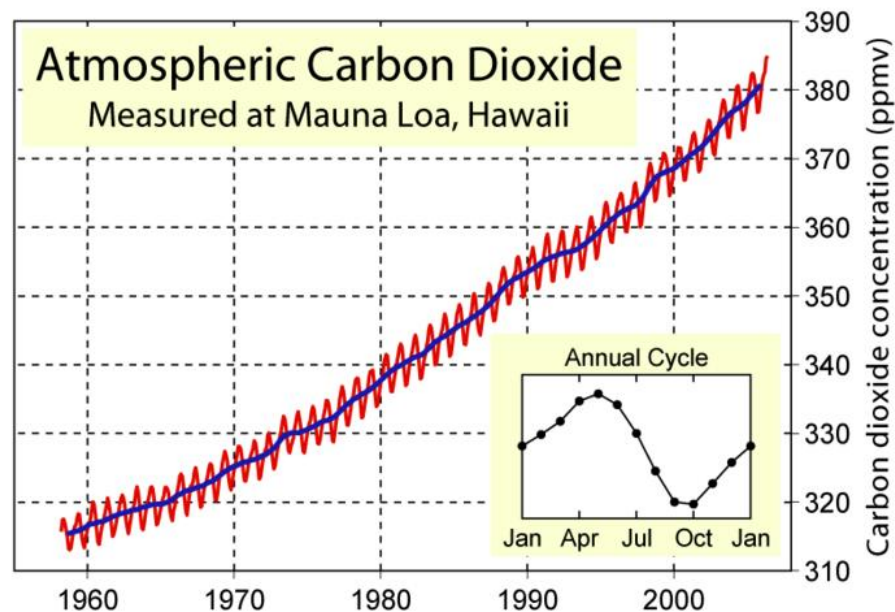
Figure 3.31: The 'Keeling Curve' of atmospheric carbon dioxide measurements, showing annual cycles and a steady increase.

He was asked to make just one measurement, but thought it would be more effective to make regular measurements. To the great surprise of scientists, he found that the carbon dioxide content of the atmosphere varied annually. He also found that, in addition to this annual variation, it also showed a steady increase, as can be seen in Figure 3.31.

The annual variations in the '**Keeling Curve**', as it has now been called, are explained because of seasonal variation of uptake of carbon dioxide by plants. There is more land, and so more plants in the Northern Hemisphere than in the Southern Hemisphere. So when, in the Northern Hemisphere summer, plants are most active, they remove carbon dioxide from the atmosphere; thus the curve reaches its lowest point at the end of the Northern Hemisphere summer, in October. It then recovers, to reach its highest point at the beginning of the Northern Hemisphere summer, in May. This annual cycle is sometimes described as the 'breathing' of the Earth.

As described above, most scientists believe that the steady increase of carbon dioxide, shown by the curve over the past 50 years, is the result of the burning of carbon-rich fossil fuels by humans, ie. it is an anthropogenic effect (anthropo - human; genic - caused by). However, some scientists think that global warming of the oceans releases carbon dioxide causing this increase - so the debate continues. However, without the crucial work of Keeling, who first demonstrated that the carbon dioxide content of the atmosphere is increasing, such a debate couldn't have taken place.

One of the most highly debated hypotheses of the climate change debate is the '**Gaia Hypothesis**' proposed by James Lovelock in the 1970s. Lovelock, working with Lynn

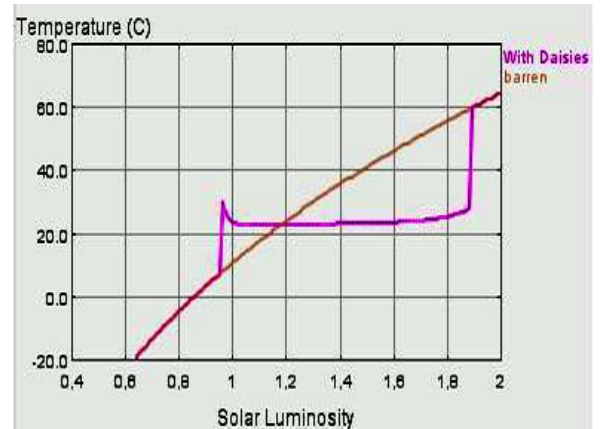Figure 3.32: A photograph of James Lovelock, taken recently.

Figure 3.33: One of James Lovelock's 'Daisyworld' simulations, showing that life could maintain a steady temperature on a planet, as solar radiation increases.

Margulis, proposed that the Earth works like an organism in that it has many negative feedback systems that maintain the conditions needed for life on Earth, and that these feedback systems are related to life. So the hypothesis proposes that life itself regulates the planetary conditions of the Earth to keep them suitable for life. Before Lovelock's proposal, most scientists thought that it was coincidence that the conditions on Earth were suitable for life, which is why the 'Gaia Hypothesis' is such a revolutionary idea and has promoted such scientific discussion.

When Lovelock found that many scientists disagreed with his ideas, he devised a computer simulation to demonstrate how the 'self-regulation' of the Earth suggested by the 'Gaia Hypothesis' could work. He called this simulation 'Daisyworld' which is based on a planet like a cloudless version of the Earth, with a Sun, like our Sun, where solar radiation increases over time. His 'Daisyworld' had only two organisms, a white daisy and a black daisy. In the early days of 'Daisyworld' the Sun was fairly cool and there was little solar radiation. At this stage, 'Daisyworld' was almost completely colonised by black daisies that could absorb all the radiation available and survive. As the temperature of 'Daisyworld' increases, the black daisies near the equator absorb too much radiation, become too hot and die, and so are replaced by the white daisies that reflect radiation and stay cool. As 'Daisyworld' becomes still warmer, white daisies replace back daisies more and more until the planet is completely covered by white daisies that keep it as cool as possible. Through this interaction of life with solar radiation, conditions suitable for 'daisylife' were maintained much longer than they would have been if the negative feedback caused by the change in the colour of the daisies had not taken place, as shown in Figure 3.33. Later Lovelock extended these computer simulations by incorporating daisies of other colours and later, rabbits to eat the daisies and foxes to eat the rabbits. Despite the increasing complexity, the results were always the same, that the life on the planet extended the time when the conditions suitable for life were maintained as the solar radiation increased.

Lovelock extended his 'Gaia Hypothesis' to include all the natural systems active on Earth, arguing that all of these must be moderated by the effects of life, since not only does life need an optimum temperature to survive, but it also needs optimum salinity in the oceans, optimum percentages of gases in the atmosphere (including carbon dioxide), optimum levels of trace elements in soils, etc. He argued that, since life on the planet moderated these conditions, like organisms moderate conditions in their own bodies (such negative feedback conditions in organisms are called homeostasis) then the planet itself also has a form of homeostasis, and can be likened to a 'superorganism'. It was when Lovelock suggested that the Earth itself acts like a living organism in some ways that many scientists disagreed with him, and many do to this day. However, his ideas have been taken seriously and tested by many scientists across the planet and, whilst they don't all fully support the 'Gaia Hypothesis' their studies have developed a new branch of science called 'Earth System Science'. '**Earth system science**' investigates the Earth as a series of systems that interact with one another and seeks to discover how these interactions can have both positive and negative feedback effects in certain conditions. It has helped us to generate computer climate models of increasing complexity, that will enable us to predict, with increasing certainly, how the global climate might change in the future.

At the moment, James Lovelock is just seen as a very important scientist in the climate debate. In future he might be considered to be one of the 'giants' of 'Earth science', like Hutton, Darwin, Wegener and Tuzo Wilson.