Basic Books in Science

Book 6

The planet we live on: The beginnings of the Earth Sciences

Chris King

BASIC BOOKS IN SCIENCE – a Series of books that start *at the beginning*

Book 6

The planet we live on - the beginnings of the Earth Sciences

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Books in the Series will be available *–free of charge–*from the websites
<www.paricenter.com> (see 'Basic Books in Science')
<www.learndev.org> (see 'For the Love of Science')

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Acknowledgements

In a world increasingly driven by information technology and market forces, no educational experiment can expect to make a significant impact without the availability of effective bridges to the 'user community' – the students and their teachers.

In the case of "Basic Books in Science" (for brevity, "the Series"), these bridges have been provided as a result of the enthusiasm and good will of Dr. David Peat (The Pari Center for New Learning), who first offered to host the Series on his website, and of Dr. Jan Visser (The Learning Development Institute), who set up a parallel channel for further development of the project with the use of Distance Learning techniques. The credit for setting up and maintaining the bridgeheads, and for promoting the project in general, must go entirely to them.

Education is a global enterprise with no boundaries and, as such, is sure to meet linguistic difficulties: these will be ameliorated by the provision of translations into some of the world's more widely used languages. We are most grateful to Dr. Angel S. Sanz (Madrid), who has already prepared Spanish versions of the first few books in the Series: these are being posted on the websites indicated as soon as they are ready. This represents a massive step forward: we are now seeking other translators, at first for French and Arabic editions.

The importance of having feedback from user groups, especially those in the Developing World, should not be underestimated. We are grateful for the interest shown by universities in Sub-Saharan Africa (e.g. University of the Western Cape and Kenyatta University), where trainee teachers are making use of the Series; and to the Illinois Mathematics and Science Academy (IMSA) where material from the Series is being used in teaching groups of refugee children from many parts of the world.

All who have contributed to the Series in any way are warmly thanked: they have given freely of their time and energy 'for the love of Science'. Paperback copies of the books in the Series will soon be available, but this will not jeopardize their free downloading from the Web.

Pisa 10 May 2007 Roy McWeeny (Series Editor)

Chris King would like to thank Stephen Davis of Geopix, who kindly supplied some of the images, and Elizabeth Devon, Dee Edwards, Peter Kennett, Pete Loader and Dave Williams for their very helpful comments on early drafts of this book. Without their contributions, the book wouldn't be as accessible and accurate as it now is - however any remaining errors are mine. Many of the images used were sourced from copyright-waived internet sites, since funding was not available to purchase images from other sources - for this reason the quality of the images, and the style of some of the diagrams used, is

variable. The sources of all the images are acknowledged in the final pages - many thanks to all those who made them available, particularly Stephen Davies from Geopix and Peter Kennett from the Earth Science Education Unit. I am also hugely indebted to Henry Law for technical and editorial support and for managing the layout of the text, and to my wife Phoebe and my family, for putting up with me during the writing.

Manchester, October 2010 Chris King (Author)

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BASIC BOOKS IN SCIENCE

– a Series of books that start *at the beginning*

About this Series

All human progress depends on **education**: to get it we need books and schools. Science Education is especially important.

Unfortunately, books and schools are not always easy to find. But nowadays all the world's knowledge should be freely available to everyone – through the Internet that connects all the world's computers.

The aim of the Series is to bring basic knowledge in all areas of science within the reach of everyone. Every Book will cover in some depth a clearly defined area, starting from the very beginning and leading up to university level, and will be available on the Internet *at no cost to the reader*. To obtain a copy it should be enough to make a single visit to any library or public office with a personal computer and a telephone line. Each book will serve as one of the 'building blocks' out of which Science is built; and together they will form a 'give-away' science library.

About this book

This book, like the others in the Series, is written in simple English – the language most widely used in science and technology. It provides an introduction to the study of 'Earth science', but 'Earth science' is interpreted differently in different countries. In some regions of the Earth, such as on the Pacific margins, it usually covers all the science relating to the Earth, including geology, meteorology, oceanography, geomorphology and soil science. It therefore covers much of physical geography in these regions, where geography is often not a strong school subject. In other countries 'Earth science' has a rather narrower definition, largely covering only geology, whilst other aspects of 'Earth science' are covered in geography. Nevertheless, wherever on Earth this book is being read, if you want to study 'Earth science' in Higher Education, at College or University, you will study mainly geology. So this book has been written as an introductory guide to geology, to interest you in the subject and to enthuse you to study geology at higher levels.

The study of geology takes many forms, but the way that most geologists begin their work is to interrogate the Earth for clues about Earth processes, in the past, present and future. This is the approach of the 'rock detective', looking for clues that will answer scientific questions about the Earth. Answering some questions always poses other questions, and so the study of geology continues ....

Notes to the Reader.

- When Chapters have several Sections they are numbered so that “Section 2.3” will mean “Chapter 2, Section 3”.
- Important ‘key’ words are printed in **boldface**: they are collected in the Glossary at the end of the book.
- You will find some parts of the text in a blue colour. In an electronic version of this book, clicking with your computer mouse on these blue sections takes you straight to the section referred to in the blue text.

Looking ahead – If you came across a cliff face on a mountain, in a coastal area or in a cutting or old quarry, and it was made of interesting-looking rocks - how could you find out more? The first Chapter of this book will help you to learn to 'read' a rock face, by finding out about the minerals that make up the rocks and how they are formed. Then you will be introduced to how the rocks themselves were formed, in sedimentary, igneous and metamorphic ways. When you know how rocks formed, you can understand how they were often later deformed, usually deep within the Earth. As these things happen to the rocks, they retain clues of the order of the events, allowing us to work out the sequence of processes and thus the geological histories of whole areas, as well as what might happen next.

The landscape also contains clues to how it formed, so by standing on a hill with a good view, you will see evidence of the underlying rock structure and how this has controlled the shape of the land. You can see clues to the processes that are still active there and the ways that the land is being used by humans. This approach, covered by Chapter 2, is another way of interpreting the evidence of your own observations to find out 'how the Earth works' now and in the past. In doing these you will be applying some of the 'big ideas' of geology, outlined in Chapter 3. Ideas about the rock cycle developed from the 1700s onwards but it wasn't until the 1960s that the theory of plate tectonics was understood, explaining many aspects of the Earth that scientists hadn't been able explain before then. In the 21st century, 'climate change' and the supply of raw materials are the most important areas of geoscientific study, helping us to understand how we will need to live on Earth in the future. Important threads that hold studies of these issues together are an understanding of geological time related to the evolution of life, and how the Earth changed in the past through plate tectonic movement, as in Chapter 4.

The basic understanding developed through Chapters 1 to 4 allows you to respond to the Chapter 5 coverage of media reports about geoscience events. The media often report events that might affect you directly, such as Earth hazards and local quarrying and landfill sites, as well as longer term issues on which you might have an impact, such as in 'climate change'. The media often report spectacular fossil finds as well, also covered by Chapter 5. This builds up to Chapter 6, covering what geologists actually 'do' today. Here you can get a feel for what an oil geologist and a mineral prospector does and how we look for underground water. Find out about the vital work that geologists do in construction and in conserving the environment and finally visit the applied and 'blue skies' studies carried out by research geologists. Through this final Chapter, you will gain a taste of what a working geologist does from day to day - and this might encourage you to carry your geological studies further.

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Chapter 1

Reading rock exposures: how rock exposures contain evidence of how they were formed and subsequently deformed

1.1 Rock exposures are formed of minerals, rocks and fossils

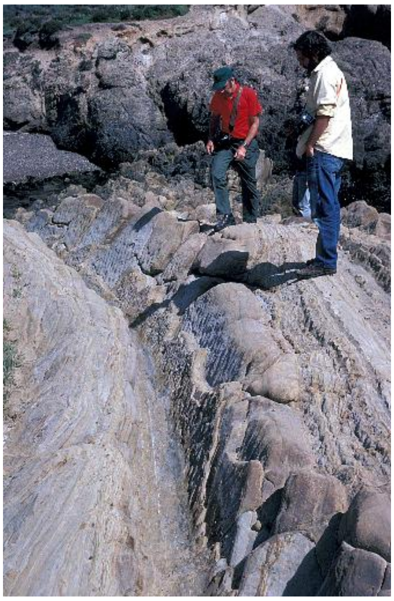


Figure 1.1: Studying a rock exposure.

Rocks and rock faces can look complicated, but this chapter will help you to 'read' rocks and rock faces, the places where rocks are exposed at the Earth's surface. It will introduce you to the clues rocks contain about how they were formed and what they can tell us about the Earth in the past.

You will find that many of the descriptions in this chapter, and elsewhere in the book, use the words 'usually', 'mostly' and 'generally'. This is because the the world is a complex place and the world of Earth science is complex too. So, while we can identify important principles that can be applied most of the time, there are often specific instances when they don't apply. This means that the Earth scientist has to be wary of applying rigid rules, but needs to look at all the evidence before interpreting a rock, a process or an environment (Figure 1.1). The more experience you have of this approach, the easier it becomes. This book will give you the basic outline of 'how the Earth works' and help you to use the evidence you can find for yourself to see 'how the Earth works'

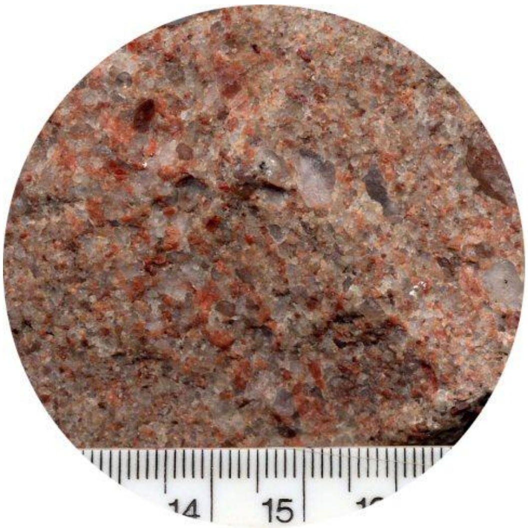


Figure 1.2: A sandstone rock - made of minerals.

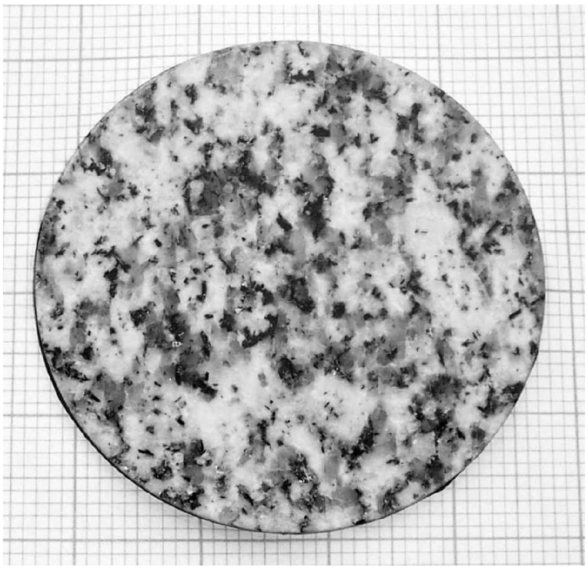


Figure 1.3: A granite rock - made of minerals.

for the different processes, rocks and landscapes you want to study.

If you look closely at a rock, either as a specimen in your hand, or forming a rock face out-of-doors, you will see that it is made of many 'bits' called grains. The grains can range from the very smallest, that are much too fine to see unless you have a microscope, to the largest grains that can be bigger than a house. See figures 1.2 and 1.3 for examples. All these grains are of just three types: they are either minerals, or other pieces of rock, or pieces of organisms, called fossils. So a definition of the term **'rock'** is 'A naturally occurring material composed of minerals, fragments of rock, or fossils.'

To make sense of this definition, we need to understand what minerals and fossils are, as well as how one rock can be made of pieces of other rocks. **Minerals** can be simply defined as 'Naturally occurring inorganic compounds or elements' whilst **fossils** are 'Traces of organisms preserved in rocks (usually more than 10,000 years old)'. But these definitions just tell you what they are; we need much more insight into how they form and what they can tell us, if we are to be able to 'read the rocks' successfully.

The chemical composition of a rock depends on the minerals it contains. The ways in which the mineral grains are fitted together is the **texture** of the rock. Rocks also have larger scale features, called structures, that will be discussed later.

1.2 Minerals are formed in a number of geological environments

Minerals are naturally formed elements and compounds and, as the first Chapter of 'Basic Books in Science' Book 5, 'Atoms, Molecules and Matter: The Stuff of Chemistry', tells

Figure 1.4: A crystal of the mineral diamond.

Figure 1.5: Crystals of the mineral calcite.

us, everything is built of atoms. A collection of atoms of just one kind is called a chemical element. When atoms combine together they form molecules and molecules of different chemical elements combined together are called compounds.

An example of a mineral formed of one chemical element is diamond, which is made entirely of the element carbon (designated: C). **Diamond** (Figure 1.4) is of course a rare mineral, which is why it is so expensive. A much more common form of carbon in the Earth's crust is the molecule calcium carbonate (formed of one atom of carbon, C, with one atom of calcium, Ca, and three atoms of oxygen, O, designated as $CaCO_3$). The most common form of the compound calcium carbonate in the crust is the mineral **calcite** (Figure 1.5).

The pictures show that both these minerals have clear shapes, called crystal shapes. This is because atoms of chemical elements in all minerals are bonded together like building blocks to form an atomic structure, and the atomic structure of each mineral is different. 'Bonds' are the forces that join the atoms of chemical elements together. In diamond, the carbon atoms form a symmetrical three-dimensional crystal structure with strong bonding in all directions, which is why diamond is so hard. However, in calcite, the atomic structure is less symmetrical, and so the shapes of the crystals are different. As some of the bonds are weaker, calcite is not as hard as diamond and can break much more easily.

In the natural world, chemical compounds are not as pure as they might be in a chemistry laboratory, so that minerals often contain traces of other elements which change their structure and properties. Thus a more complete definition of a mineral is: 'A naturally occurring inorganic compound with a definite chemical composition, a definite atomic structure, and physical properties which vary between known limits'.

One of the physical properties which quite often varies is colour, particularly in the paler-coloured minerals so that, whilst calcite is usually colourless or white, it can have grey, yellow, blue, red, brown or black tints, depending on which trace elements it contains.

Even diamond can have different colours, although colourless diamonds are usually the most valuable.

We use the properties of minerals to identify them, and the most useful properties are their colour, which depends on their chemical composition, and their shape, **hardness**, and the way they break (**cleavage**), which depend on their atomic structures. Certain minerals also have other properties, which help us to identify them. We can use how heavy they feel (their density), their surface appearance (their lustre) or the colour of their powder (their **streak** left as a scratch on a white tile), whilst some react with acid, are soluble or are magnetic.

Common minerals that you can identify using these properties are listed at the end of this section.

Minerals form in only five common ways and you can usually use the clues they contain to find out how they crystallised. They form by:

- crystallising from molten rock as it cools
- recrystallising due to increases in heat and/or pressure
- crystallising from evaporating water
- crystallising from liquids flowing through the pores in rocks
- crystallising from hot fluids that cool as they flow through rocks

1.2.1 Igneous rocks

When rock becomes very hot, more than 600°C, the minerals begin to melt and nearly all minerals have melted by a temperature of 1800°C. As the minerals melt, the atoms and molecules they contain are released to form a 'bath' of liquid called **magma**. This liquid mixture of atoms and molecules is usually less dense than the surrounding rock and so tends to rise. As magma rises, it cools down, so that minerals begin crystallising again. As cooling continues, the first crystals to form become larger, as more molecular building blocks come together and the atomic structures grow. The longer the liquid has to cool, the larger the crystals become. Eventually all the liquid crystallises and the rock has become a solid mass with a texture of randomly-orientated interlocking crystals. Rocks formed by crystallising from magma are called **igneous rocks**. Most magmas crystallise underground, but if magma flows to the surface it is called **lava**. So solidified lavas are also igneous rocks.

The most common minerals found in igneous rocks are quartz, a compound of silicon and oxygen (SiO_2) with a simple but well-bonded atomic structure, and feldspar, another silicon/oxygen (silicate) compound but with extra aluminium, sodium, potassium and calcium, and with an atomic structure that is nearly as well bonded as quartz. A third common mineral is mica, another silicon/oxygen compound with extra elements added; this is poorly bonded, particularly in one direction, and so has a strong cleavage, is soft and layers are easily broken off. In igneous rocks, quartz is grey, feldspar is white or

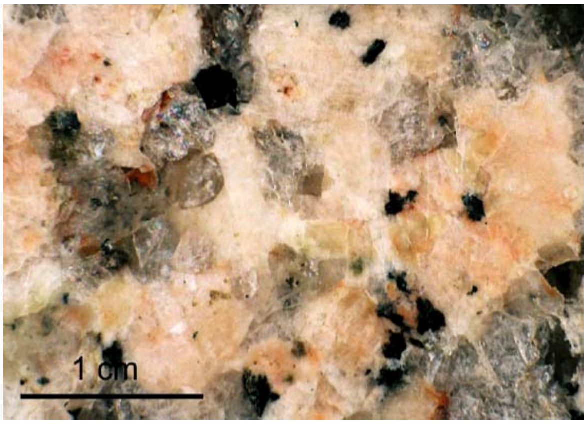


Figure 1.6: A close up view of a piece of the igneous rock, granite.

Figure 1.7: A close up view of a piece of the metamorphic rock, gneiss.

sometimes pink, and mica is black or colourless. You can see all these minerals in the photograph of granite (Figure 1.6), which also shows how the minerals have crystallised to fill all the space, in a tough interlocking texture.

1.2.2 Metamorphic rocks

When rocks are heated or come under great pressure, the minerals in them can be recrystallised without melting and this recrystallisation process is called **metamorphism**. During metamorphism the sizes and shapes of the original minerals can be changed or original minerals can be changed into new minerals. The result is a tough rock with an interlocking texture. If the metamorphism is caused by high temperature alone, then the new metamorphic minerals have random orientations. However, if the metamorphism is caused by high temperatures and pressures in the roots of mountains during mountain-building episodes, the metamorphic minerals recrystallise at 90° to the direction of the pressure. In high pressure/temperature metamorphic rocks, many of the minerals are therefore aligned into a rock texture of sheets or bands, as seen in the photograph in Figure 1.7.

The minerals quartz, feldspar and mica found in igneous rocks are also common in metamorphic rocks, but a mineral that is not frequently found in other rocks, but is common in higher grades of metamorphic rock, is garnet. **Garnet** (Figure 1.8) is another silicate mineral, where the silicon/oxygen has combined with aluminium and calcium, iron or magnesium. It has a strongly-bonded structure making it a hard mineral. Due to this hardness and its pleasing red or pink colours, it is sometimes used as a semi-precious gem mineral.

If the metamorphosed rock was originally made of calcium carbonate (i.e. limestone), then the rock produced by metamorphism is also composed of the calcium carbonate mineral, calcite. The new rock, formed of interlocking calcite crystals, is called **marble** (Figure 1.9).

Figure 1.8: A red garnet crystal in a metamorphic rock.

Figure 1.9: Marble, a metamorphic rock made of interlocking calcite crystals.

Figure 1.10: Salt deposited by evaporation of a drying lake.

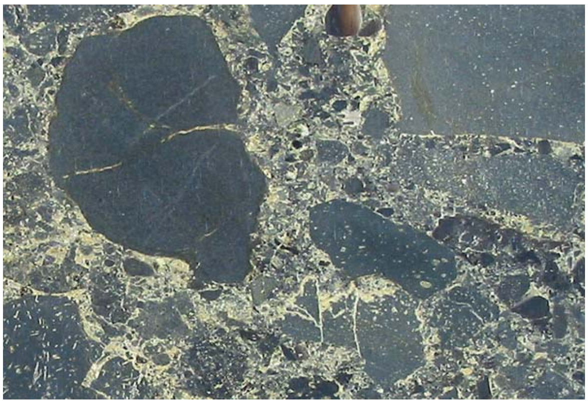


Figure 1.11: A sedimentary rock, showing the fragments ‘glued’ together by a natural cement.

1.2.3 Evaporites

When salt water evaporates as lakes or arms of the sea dry out, salts crystallise out as deposits that cover the old lake or sea bed (Figure 1.10). These are called **evaporite deposits** and the most common of these is the compound of sodium and chlorine, **halite**. The sodium chloride (NaCl) molecules are weakly bonded, so halite is a mineral with a very low hardness. The sodium chloride bonds are broken in water so that halite is soluble and easily dissolves again. Because of this solubility and its salty taste, a refined form of halite is used as table salt in many of the foods you eat. If you want to crystallise your own salt crystals, see the 'Salt of the Earth: Who can make the biggest salt crystal?' activity on the `http://www.earthlearningidea.com` website.

1.2.4 Sedimentary rocks

Sedimentary rocks are made of sediments which are fragments of other rocks or fossils, although sometimes sediments can also be laid down by the evaporation of water. Often the grains of sediment are single crystals which have been broken and worn down. These have often become **rounded** during transportation and **sorted** into grains of similar sizes. After they have been deposited, water flows in the **pore spaces** between the grains. This slow-flowing water dissolves minerals from some parts of the deposit and they recrystallise between the grains in other parts of the deposit, 'gluing' the grains together. This natural 'glue' is called **cement** and changes soft sediments into harder sedimentary rocks (Figure 1.11).

The most common cementing minerals in sedimentary rocks are quartz and calcite. As the pore spaces become filled with cement, the tougher the rocks become. Try the 'Make your own rock' activity on the `http://www.earthlearningidea.com` website to find out how this cementing process works.

1.2.5 Veins and ores

Sedimentary rocks are cemented by cool fluids. However, magmas can produce hot watery fluids, whilst in other areas where rocks are heated, the water in the rocks can dissolve minerals. This watery hot liquid containing dissolved minerals is a **hydrothermal fluid** that, being less dense than the surroundings, rises through pore spaces and cracks in the rock. As it rises it cools and minerals crystallise out of solution in the pore spaces or as coatings on the sides of the cracks. Mineral-coated cracks are called mineral veins. These can be thin sheets that fill a fracture such as a joint in a rock, or more complex sheets filling faults or other fractures and spaces.

Quartz and calcite commonly crystallise in mineral veins, but sometimes more unusual minerals can form (Figure 1.12). If mineral deposits contain metal minerals and the deposits are rich enough to be worth mining, the deposits are called **metal ores**. **Ore minerals** include the red iron oxide (Fe_2O_3) mineral hematite, and the shiny grey, lead sulfide (PbS) mineral galena. In deposits of ore minerals, the uneconomic minerals that have to be thrown away, like quartz and calcite, are called **gangue minerals**.

Figure 1.12: Crystals of minerals in a mineral vein.

Figure 1.13: The red ore mineral hematite with the colourless gangue mineral, calcite

The most valuable minerals are the precious gemstones like diamond, which are hard and rare. Diamond is found in certain volcanic deposits, or has been eroded from them and deposited in rivers and beaches. Semi-precious stones which are fairly hard and rare include garnet and the coloured forms of quartz found in some mineral veins, like purple amethyst quartz.

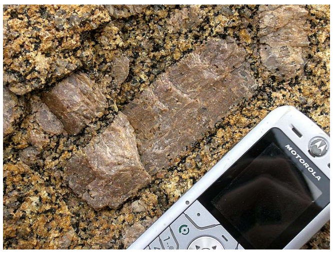
Metallic minerals like hematite (Figure 1.13) and galena, can form valuable ore deposits, but one of the most valuable metal minerals is gold. Gold is an un-reactive element that rarely combines with other elements and so is usually found on its own as native gold. **Native gold** can be found in mineral veins or, like diamond, eroded from veins and deposited in sediments.

Minerals can be identified by their properties; some important minerals are shown in figures 1.14 and 1.15.

Calcite, $CaCO_3$ - usually white or colourless, can form good ‘dog tooth’ crystals, good cleavage, fairly low hardness, reacts with dilute acid, is the main mineral in marble and in some sedimentary rocks (limestone) and is found as a gangue mineral in veins

Diamond, C - usually colourless, forms good crystals, extremely hard, rare

Feldspar, silicate - white or pink, can form good rectangular crystals, good cleavage, hard, common in igneous and some metamorphic rocks



Garnet, silicate - usually red or pink, often forms ball-shaped crystals, no cleavage, hard, found mainly in medium and high grade metamorphic rocks

Gold, Au - gold colour, usually irregular shape, feels very dense, low hardness (soft), rare. The picture shows a very unusual example of a large gold nugget, rounded because it was found in stream sediment.

Figure 1.14: Some important minerals and their identification properties

Hematite, Fe_2O_3 - earthy red, metallic lustre, feels dense, red streak, usually hard, often found in irregular masses. The picture shows its reddish colour and metallic lustre

Halite, NaCl - white or pink, cube-shaped crystals, good cleavage, low hardness (very soft), soluble in water, forms rock salt deposits. The picture shows pink halite crystals in a rock salt deposit.

Galena, PbS - silvery grey, metallic lustre, cube-shaped crystals, good cleavage, feels very dense, grey streak, low hardness (soft), found in mineral veins; the picture shows silvery-grey cubic galena crystals with their metallic lustre, with a pale gangue mineral.

Mica, silicate - usually colourless or black, forms platy crystals, good cleavage in one direction, low hardness (soft), common in igneous and some metamorphic rocks

Quartz, SiO_2 - usually grey, white or colourless, can form good hexagonal crystals, no cleavage, hard, common in sedimentary, igneous and metamorphic rocks and as a gangue mineral in veins

Figure 1.15: Important minerals - 2

1.3 Sedimentary rocks - formed by a range of surface processes in a variety of environments

You can 'read' sedimentary rock exposures by understanding that these rocks were once loose sediments that have been cemented or compressed into sedimentary rocks. They therefore contain the same clues that sediments do, to the ways in which they were originally moved and laid down. These clues include the size, shape and chemical makeup of the grains, the layers these grains form, like the cross bedding in Figure 1.16, and the fossils and overall sequences that the rocks contain. Since most sedimentary rocks have layers, called **beds** (see Figure 1.17), you can usually use this to distinguish them from igneous and metamorphic rocks. The good 'rock detective' can read sedimentary rock clues of composition (chemical makeup), texture (grain size, shape and arrangement) and **structure** (including structures like bedding and **cross bedding**) to discover the environment in which the sediments were first deposited.

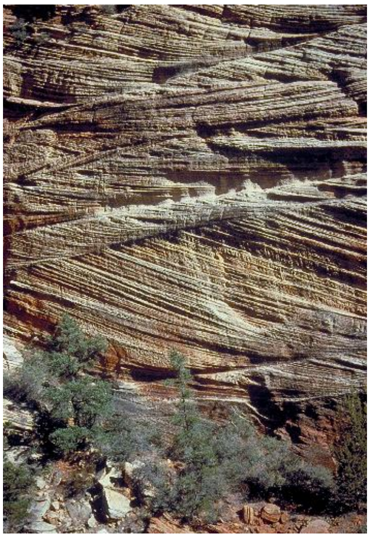


Figure 1.16: A sedimentary rock face showing some of the clues into how the sediments were originally laid down.

Sediments are generally eroded from higher land and deposited in lower areas. Such lower areas include puddles, ponds, lakes, gutters, streams, rivers, valleys, general lowland areas, coastlines and shallow and deep seas. These lower areas span a range of latitudes, from polar to temperate to arid and tropical. Deposits of boulders, gravel, sand or mud can be laid down at all latitudes but calcium carbonate deposits (limestones) and evaporites are formed mainly in the tropics.

Most sediments are formed from the weathering and erosion of rocks, which could be of sedimentary, igneous or metamorphic type. Deposits near these source rocks have not been moved very far and so the make up of the sediment is similar to the mineral composition of the source rocks. If the source rocks contained quartz, feldspar and mica, so will the sediment. Similarly, there has been little chance for the sediment to become sorted into different grain sizes or for the grains to be worn down. Thus, sediments near source rocks usually have mixed compositions and mixed sediment sizes, whilst the individual sediment fragments have sharp corners and are angular, as in Figure 1.18, which shows a **breccia** (a sedimentary rock of mixed sizes with angular grains).

Gravity moves these sediments downhill and they become picked up by water and moved along streams and into rivers. Minerals like mica, and later, feldspar, become broken down. The corners of individual grains are worn away and they become rounded and reduced in size. The abrasion of the grains to smaller sizes and rounded shapes is called **attrition**. As rivers and later, coastal currents, carry the grains along, they are sorted into different sizes, since fast flows can carry large grains whilst small grains only settle

Figure 1.17: Sedimentary rocks showing their layers or beds. The surface of each bed is called a bedding plane.

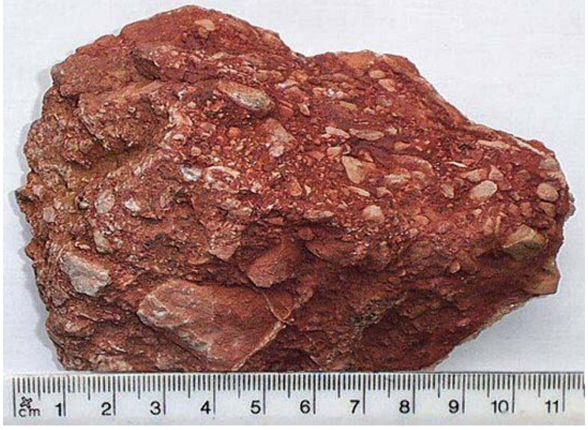


Figure 1.18: A sedimentary rock made of angular fragments, a breccia.

in quiet conditions. So, we find boulders, pebble deposits, sand deposits and deposits of mud in different parts of rivers and coastal areas, depending upon the speeds of current flow. The proportion of quartz in sediments increases as they are carried along, since mica and feldspar are broken down physically and chemically. The chemical breakdown of mica and feldspar produces **clay minerals** so there is a high proportion of these very fine-grained minerals in quiet areas of deposition.

So, we can use the sizes, shapes and compositions of the grains to tell us about how the grains were transported and deposited. Poorly-sorted angular sediments of mixed compositions are found near source areas, whilst well-rounded gravel deposits, well-sorted, quartz-rich sands, and muds rich in clay minerals, are found far from their sources. The gravels can become cemented into **conglomerates** (Figure 1.20), the sands into **sandstones** (Figure 1.21) and the muds can later be compressed into **mudstones** (Figure 1.19) and **shales** (shales are weak mudstones that tend to fall apart in your hand).

Deserts are mostly very dry but sometimes have torrential storms, so we can find a wide range of deposits. There are accumulations of angular fragments that could become breccias, whilst dried rivers can have pebble and sand deposits that could become conglomerates and sandstones (Figure 1.22). Dried up lake beds can have muds and salt deposits (as in Figure 1.23) that could be preserved as mudstones with evaporite layers. These deposits often contain more clues as well.

Most of the sands have layers that will become sandstone bedding. When sands are deposited in fast flowing rivers, they are usually laid down in small underwater **dunes** as sloping layers that are seen as the cross beds in many sandstones. Since the cross beds always slope downstream, they tell you the direction of the current flow that laid down the sand (as in Figure 1.24). As water currents slow down, the surface of the sand often forms into current ripple marks that have a shallow up-stream slope and slope more steeply downstream. These **asymmetrical ripple marks** or **current ripple marks** tell you the direction of the current that deposited them and these can be preserved in

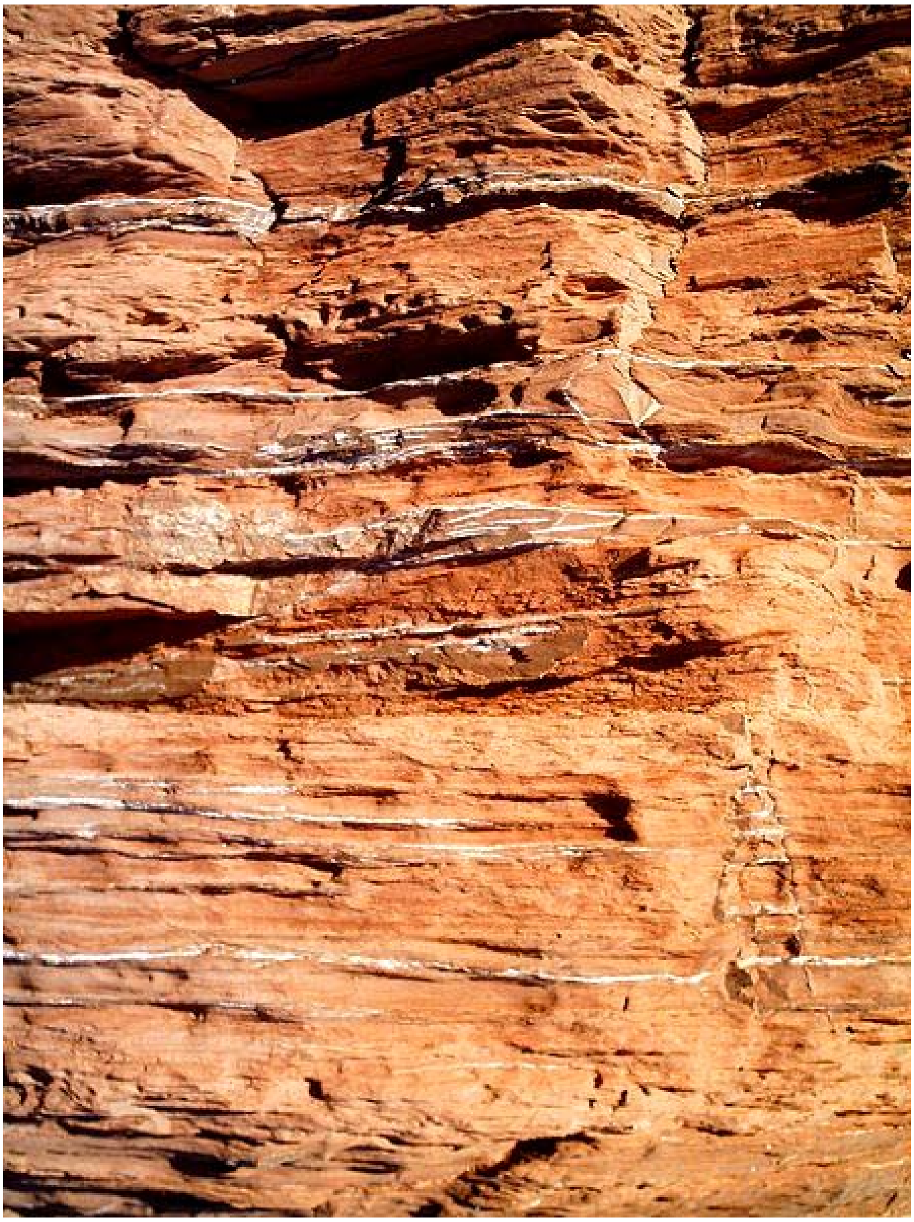


Figure 1.19: The fine grained sedimentary rock mudstone, in a cliff face.

Figure 1.20: A close up view of a piece of conglomerate, a sedimentary rock made of rounded pebbles cemented together.

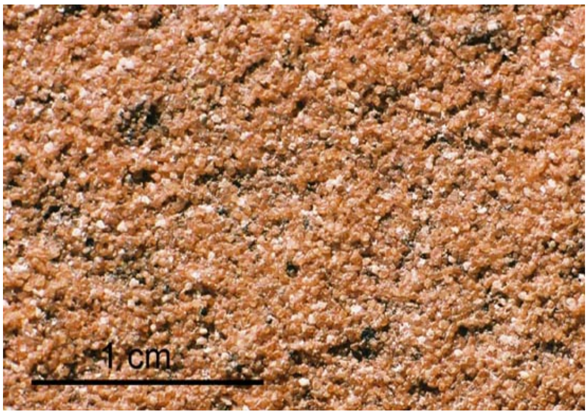


Figure 1.21: A close up view of a piece of sandstone, made of cemented sand grains.

Figure 1.22: The angular fragments of sediment in a desert that could become a breccia.

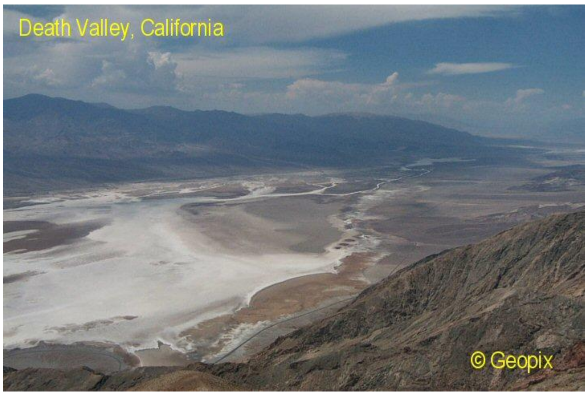


Figure 1.23: Dried up lake bed with white salt deposits in a desert environment - Death Valley, California.

rocks. Many of these desert deposits are red, because the weathering processes there tend to concentrate red hematite on the surfaces of sediment grains. You can investigate how water currents move and deposit sand using the 'Mighty river in a small gutter: sediments on the move' activity from the `http://www.earthlearningidea.com` website.

Figure 1.24: Cross bedding in sandstones. The water flow direction here was from left to right

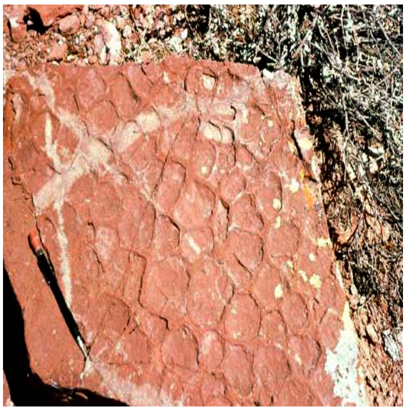


Figure 1.25: Ancient mud cracks preserved in mudstone.

Each time mud settles out from quiet water, in a desert lake, for example, it forms a layer. These layers build up into series of **laminations**. If the mud dries out the surface shrinks and it breaks into **mudcracks** (desiccation cracks) with polygonal shapes (Figure 1.25). Since mudcracks only develop in dried mud, mud cracked mudstones show that the mud could not have been deposited in the sea - which would not dry out. The mud sometimes carries other clues that it dried out, such as small pits made by raindrops or footprints of the creatures that lived there at the time. If salt was deposited on the drying lake floor, the mud can preserve the shapes of the cube-shaped crystals. The next mud layer can make casts of these shapes, preserving the shapes of the salt crystals in mud. All these clues of an environment that was once wet but dried out, can be preserved as the mud becomes mudstone.

If desert lakes have sandy floors then waves can form **symmetrical ripple marks** in the sand in the same way as they do on beaches and in shallow seas (see Figure 1.26). Unlike current ripple marks, these **wave ripple marks** are symmetrical, with an equal slope on either side. They are usually straight as well, and are parallel to the waves that formed them so, since waves are parallel to shorelines, they can show you the direction of the shoreline of the lake or coast when the ripples formed. Try making your own ripple marks using a washbowl (current ripples) or a tank (wave ripples) as shown on the `http://www.earthlearningidea.com` website.

Windy deserts are famous for wind-formed sand dunes. The winds were not strong enough to pick up larger particles, so they formed the sand into dunes, and blew any mud-sized particles out of the area. The sand is therefore well-sorted and has become rounded and quartz-rich as it was blown along (Figure 1.27). The grains often have red hematite-stained surfaces. Sand is laid down by the wind on the sloping fronts of the dunes in large cross beds, much larger than the cross beds found in rivers. Preserved dune cross bedding can be a metre or more high. So, desert dune deposits have well sorted, red-coloured quartz sands deposited in large sets of cross bedded sandstone (see Figure 1.28).

Figure 1.26: Ancient wave ripple marks preserved in sandstone.

Figure 1.27: Modern sand dunes, made of well-sorted sand deposited in sloping layers on the front of the dune - Death Valley, California.

Figure 1.28: Ancient dune cross bedding preserved in a sandstone cliff face.

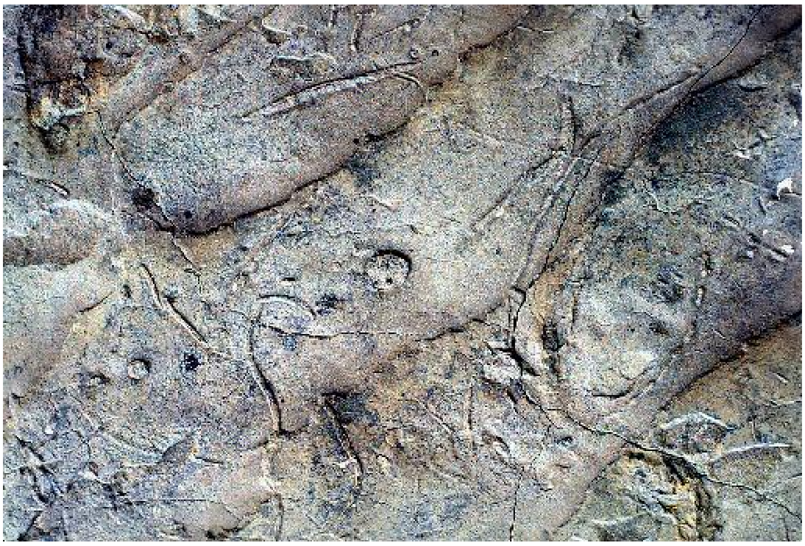


Figure 1.29: Tracks, trails and burrows preserved on a ripple-marked sandstone.

In coastal regions, gravel is deposited on shingle beaches, sand is laid down in sandy beaches and on much of the shallow sea floor, and mud is deposited on tidal flats. Beach gravel is usually easily distinguished from other sorts of gravel deposit because the pebbles have become well-rounded by the continuous pounding of waves. Beach and shallow sea sands can also be distinguished from other sorts of sand because, although they can also have bedding, cross bedding and wave ripple marks, they contain much fossil debris too, because coasts and shallow seas have great variety of life and many of the organisms have hard parts that can become fossilised. Similarly, although coastal muds can dry out and have mudcracks, footprints and rain pits, they also contain abundant life. The evidence of life can be preserved in tidal muds, not only as fossil fragments, but also as whole fossils and burrows, feeding tracks and trails (as shown in Figure 1.29).

When rivers that are loaded with sediment reach the sea, the sediment often builds out into the sea as a delta. The delta is mostly formed of sand but mud is deposited on the

Figure 1.30: Coal seams in an opencast coal quarry.

edges of the delta in the deeper regions. If the delta is in a tropical region, the delta top becomes covered in vegetation in the swampy tidal conditions. When the swamp trees die through natural life cycles, they fall and build up into thick sequences of organic material. These are the conditions in which coal forms and there are many examples in the geological record of delta sediments with coal deposits on the top. The muds of the foot of the delta are preserved as shale, above this are the thick sands of the delta itself, often deposited in large cross beds. On top of the delta sands are coal deposits, found as coal seams (see figure 1.30). Coal mining industries across the world are based on deposits like these.

Shallow tropical seas have some of the greatest variety of life on Earth and many of the organisms that live there, from microscopic algae to giant clams, have hard parts made of calcium carbonate (often calcite, but also a different form of calcium carbonate, called **aragonite**). When the organisms die, this material builds up on the sea floor as deposits that will become **limestones**. These calcium carbonate deposits are often rich in fossil debris including broken shells, pieces of coral and other carbonate debris. Since most types of coral are only found in tropical seas today, if they are preserved, we know that the environment must originally have been a tropical shallow sea. The photograph (Figure 1.31) shows a limestone made of fragments of crinoid, another animal that was common in some ancient shallow seas. Since calcium carbonate reacts with dilute acid, it is easy to distinguish limestone from other sedimentary rocks, by the one-drop **acid test**.

In shallow tropical sea areas where there is strong evaporation, another type of limestone can form. It is made of spherical grains of carbonate sand that are rolled around by the waves and tidal currents. The carbonate grains grow as the water evaporates and tiny crystals of aragonite crystallise onto the surfaces of the tiny balls. The balls are called

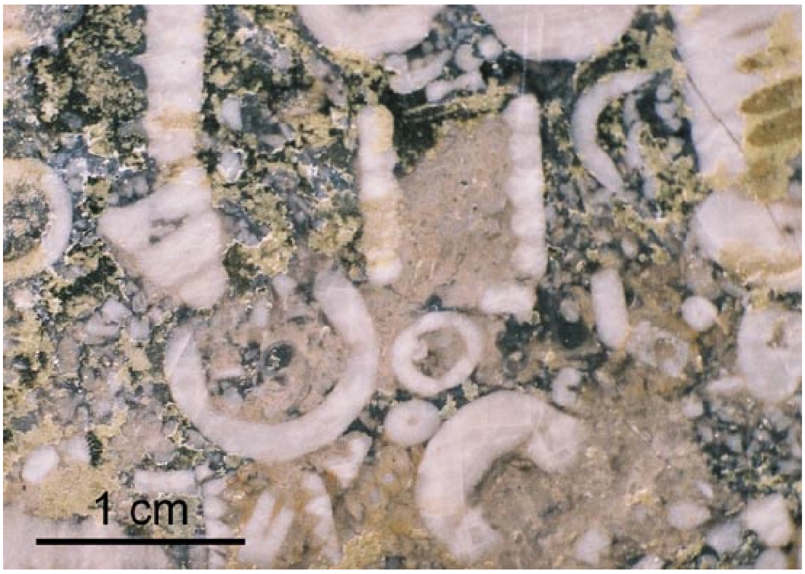


Figure 1.31: Close up view of a piece of limestone, formed of fossil fragments cemented together.

oolites and, when cemented into rock, become **oolitic limestone** (see Figure 1.32). You can easily distinguish limestones from other sedimentary rocks since, being calcium carbonate, they react with dilute acid. So the one-drop acid test causes violent fizzing.

The only sediment that is normally deposited in deep sea areas is fine-grained mud. Most of the mud was originally fine-grained sediment blown from deserts or was brought into the sea by rivers. This mud contains the remains of tiny organisms that live as plankton near the surface of the ocean and sink to the bottom when they die. The mud builds up on the deep sea floor very slowly and, when it is compressed by the overlying layers, it becomes mudstone or shale. However, where rivers bring large amounts of sediment into the sea, in deltas for example, this sandy and muddy sediment builds up on the edge of the ocean basin. An earthquake can trigger a slide of this material, which flows down into the deep sea as a billowing cloud of muddy sediment called a **turbidity current**. Turbidity currents can flow at more than 100 km per hour across thousands of square kilometers of deep ocean floor depositing flat sheets of sediment called **turbidites**; there is an example of one in Figure 1.33. Each turbidite has the coarser material, usually sand, at the bottom and becomes finer grained upwards to the mud at the top. This is a **graded bed**, coarser at the bottom and becoming finer upwards. Usually many turbidite layers build up into thick turbidite sequences on the deep ocean floor as stacks of graded beds of different thicknesses.

In cold areas, such as polar regions and high mountains, ice can erode, transport and deposit sediments. Since the ice carries material of all sizes and the particles do not become sorted or rounded as they are carried along by the ice, deposits of melting ice are easily recognised by their mixture of boulders, sand and clay. This ice-deposited mixture is called **glacial till** (Figure 1.34)and can be found across many areas of northern Europe

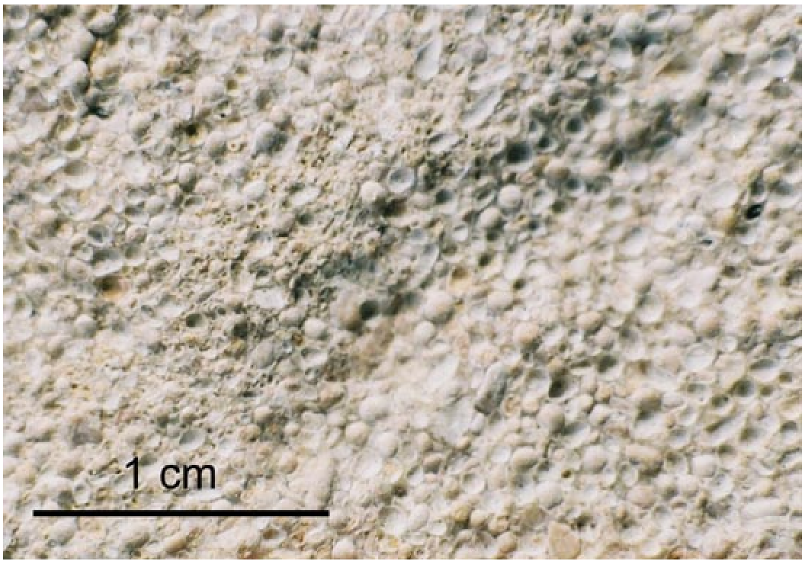


Figure 1.32: Close up view of a piece of oolitic limestone, made of tiny balls of oolite cemented together.

Figure 1.33: This sequence of turbidites has become tilted by folding of the rocks.

Figure 1.34: A melting glacier depositing glacial till.

and America, showing that these areas were covered by ice sheets in the past. Other clues to past glaciation include glacial U-shaped valleys and rocks scratched by the ice dragging rock fragments across their surfaces.

The fossils that sedimentary rocks contain can be valuable in helping us to interpret the environment in which the sediments were laid down. Where possible we use the principle that the 'present is the key to the past' (the Principle of **Uniformitarianism**) to help us to understand the ancient environment. Coral is a good example of an environmental indicator, since most coral only grows in shallow tropical seas today so, if we find fossil coral, we can assume that the sediments were also deposited in shallow tropical seas (there is a picture of a fossil coral in Figure 1.35). Similarly, land plants only grow on land or in the swampy conditions of some coastal areas, so fossil land plants, such as those in Figure 1.36, show not only that the area was land, but also, if the growth was very luxuriant and produced lots of organic material (as in coal), that the area was tropical as well. Tracks, trails and footprints are important, since they tell us that there were living things in the area and so it was not too hot, or cold, or dry, or lacking in oxygen or food for organisms to live there. Since most tracks, trails and footprints are made on dried-out land or in shallow water, they provide further clues to the environment.

When animals have become extinct, we cannot use the 'present is the key to the past' principle so easily. Nevertheless, we know that the modern relatives of fossils like trilobites (Figure 1.37) and ammonites (Figure 1.38) only live in the sea and so the sediments in which they are found are most likely to have been deposited in the sea. Likewise, the modern equivalents of trilobites live in shallow waters, indicating that most trilobites also lived in shallow sea conditions.

Sediments become sedimentary rocks after they become buried, through a process called **diagenesis** that normally takes millions of years ('millions of years' is usually abbreviated to **Ma**). As the sediments become buried by more and more sediments, they become

Figure 1.35: A fossil colonial coral preserved in shallow tropical sea sediments.

Figure 1.36: Fossilised trees that must have grown on the land.

Figure 1.37: A fossil trilobite, found in shallow sea sediment.

Figure 1.38: Fossil ammonites, indicating sediments that were deposited in the sea.

compressed as the grains are compacted together and water is squeezed out. Meanwhile waters flow through the pore spaces between the grains and minerals crystallise from the water as cement. The effect of the two processes of compaction and cementation is that the rocks become harder and the porosity is reduced. **Porosity** is a measure of the amount of pore space in the rock and, even after compaction and cementation, can still be as high as 20% in some sandstones and limestones. Since the pore spaces are large enough for water and gas to flow through, these rocks are also permeable (**permeability** is a measure of how quickly a fluid can flow through a rock). Most mudstones and shales are surprisingly often very porous, but because the pores are too small to allow fluids to flow through, they are often **impermeable**, i.e. the fluids cannot flow through the rock.

The porosity and permeability that remains in the coarser grained sedimentary rocks after diagenesis is vital, because these rocks can contain underground water supplies and oil and gas, stored in the gaps between the grains. You can investigate for yourself how rock porosity and permeability work using the 'The space within: the porosity of rocks' and the 'Modelling for rocks: What's hidden inside - and why?' practical activities from the `http://www.earthlearningidea.com` website. These show that, if you drop water on to permeable porous rocks, it will soak in, but if a drop of water is put onto an impermeable rock, it will stay on the surface. You can also distinguish a permeable from an impermeable rock by putting them both in water. You might see a few small air bubbles on the surface of the impermeable rock but many more bubbles rise from the permeable one as air bubbles rise out of the pore spaces at the top, and water flows in to fill the spaces at the bottom.

Try to get a feel for how scientists use the clues from sedimentary rocks and fossils to interpret the environments in which the sediments were deposited by using the 'What was it like to be there - in the rocky world? and 'What was it like to be there - bringing a fossil to life' activities from the `http://www.earthlearningidea.com` website.

1.4 Igneous rocks - formed from molten rock by a range of processes

Rock faces made of igneous rock can usually be distinguished from sedimentary rock faces because they have no layers, and so are described as '**massive**' (Figure 1.39). Since igneous rocks are made of interlocking crystals, they are normally tougher than most sedimentary rocks and are also impermeable, so that water runs off them, unless they are cracked or fractured.

Igneous rocks are formed from once-liquid magma. Although there may seem to be a wide variety of them, they are affected by just two main variables, their chemical composition and where in the Earth's crust they cool down and solidify.

The composition of a magma depends primarily on the composition of the rock that was melted and on how much melting took place. Rocks are formed of a mixture of minerals and these have different melting points. In general, minerals rich in iron and magnesium have high melting points, while minerals rich in silicon have low melting points. As a rock is heated, it is the minerals with the lowest melting points, those rich in silicon, that melt first. This is **partial melting**, but can also be called fractional melting, since the fraction of the rock with the lowest melting points melts first. This is similar to fractional distillation, when a mixture of liquids is heated and the different fractions change from liquid to gas at different temperatures and boil off in turn. The only difference between the processes of fractional melting and fractional boiling, is that fractional melting is a solid to liquid change that depends on the melting points of the materials involved, while in fractional distillation liquid becomes gas and depends on boiling points.

Beneath the Earth's crust is the mantle and all the material that now forms the crust originally came from the mantle. Mantle rock is relatively rich in iron and poor in silicon; it is called an **ultramafic** rock ('mafic' meaning magnesium, 'ma' and iron, 'fic'). When this becomes heated, it partially melts and, since the silicon-rich minerals melt first, the melt is richer in silicon than the original mantle rock. The new magma rises and penetrates the rock above. This is a **mafic** melt, found mainly at mid-oceanic ridges, above the mantle source rock. Mafic melts cool to form mafic rocks. Where these mafic rocks become heated again, as can happen if they are carried to oceanic trenches, they partially melt, producing a magma which is even richer in silicon, called an **intermediate** magma. If, in turn, the rocks formed by intermediate magmas are partially melted, as can happen if they are carried beneath continents, a melt even richer in silicon is formed, called a **silicic** melt. This shows that the four main different compositions of magma are produced by the partial melting of the others in sequence: ultramafic rocks partially melting to mafic melts; mafic rocks partially melting to intermediate melts; and intermediate rocks partially melting to form silicic melts and rocks.

Being hot and therefore less dense than the surrounding rocks, magma rises and intrudes into the rocks above. If it doesn't reach the surface but cools down beneath the surface, it cools slowly, since the rocks above are very efficient insulators. When magmas cool slowly there is time for the crystals to grow and so slow-cooling, deep magmas have large crystals. These are **coarse-grained igneous rocks** with easily-visible crystals. Magmas nearer

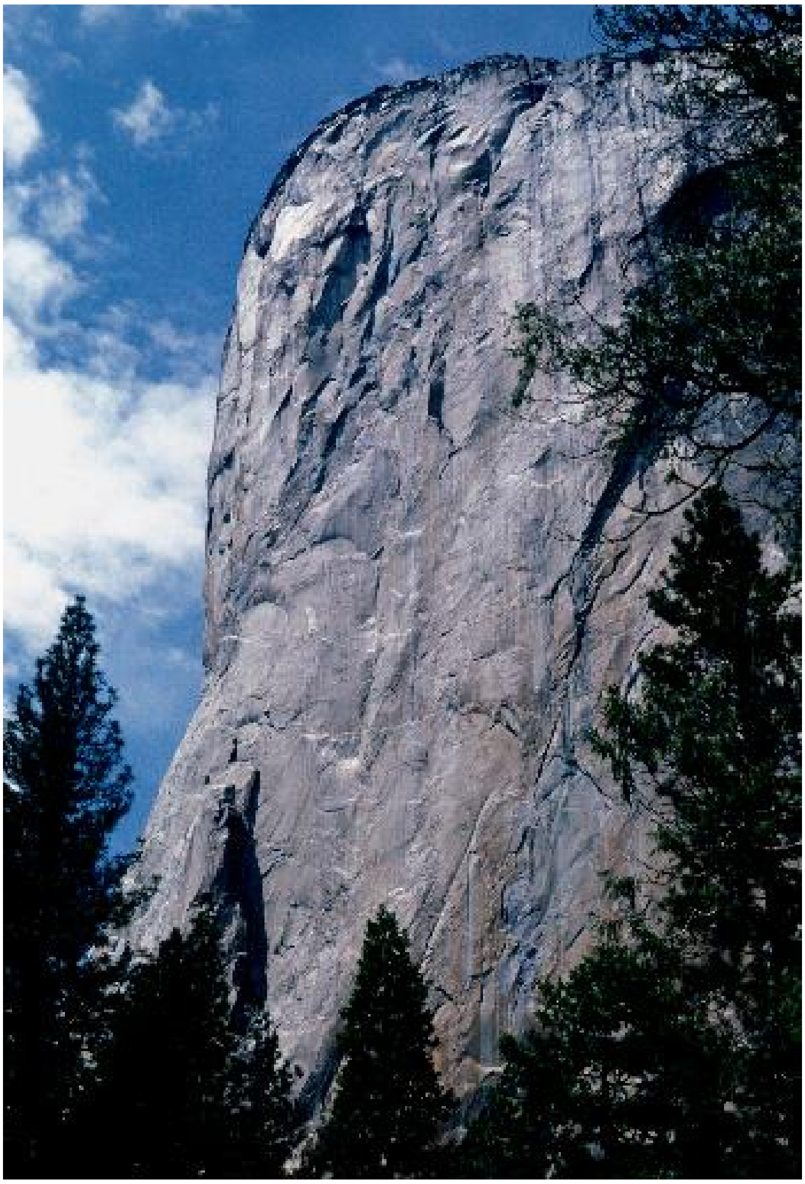


Figure 1.39: ‘Massive’ igneous rocks; a granite rock face without layers.

Figure 1.40: A close up view of a piece of gabbro.

the surface cool more quickly, forming medium-grained rocks with individual crystals that are harder to see. If magmas reach the surface, they are extruded and can flow out as lavas. Such **extrusive** igneous rocks cool down very quickly, either in the air or under water, forming fine-grained igneous rocks. The crystals in **fine-grained igneous rocks** are almost impossible to see without using a hand lens.

These processes show how igneous rocks of different compositions and grain sizes are formed. Their colour can help us to distinguish them, since the richer in silicon a rock is, the paler it is. Some igneous rocks are more common than others. The coarse-grained ultramafic rock that forms much of the mantle is called **peridotite**. A coarse-grained mafic rock, dark in colour, is called **gabbro**, shown in Figure 1.40, and its fine-grained equivalent, that forms many lava flows, is dark-coloured **basalt** (Figure 1.41). The fine-grained rock forming intermediate lavas is **andesite**, which is paler in colour than basalt. Fine-grained silicic lavas are uncommon, but the coarse-grained equivalent is very common. This coarse-grained, pale-coloured, silicic igneous rock is **granite** (Figure 1.42).

This fairly simple picture is complicated by how lavas erupt, since the composition affects the viscosity of the magma and this in turn affects the type of eruption. Mafic magmas that produce basalts are relatively rich in iron but poor in silica. Silica-poor magmas have low viscosity and these runny lavas can flow quickly out of cracks in the ground, called volcanic fissures (Figure 1.43), and spread over wide areas. Small bubbles of volcanic

Figure 1.41: A close up view of a piece of basalt with gas holes, called vesicles.

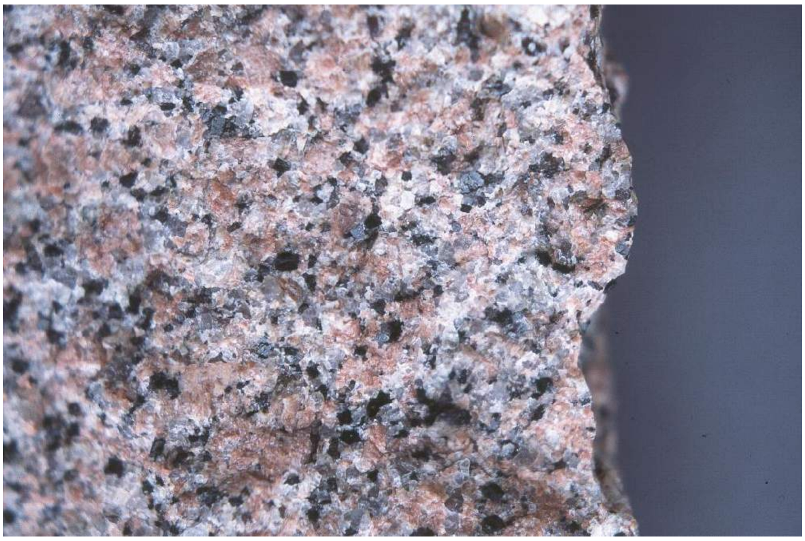


Figure 1.42: A close up view of a piece of granite.

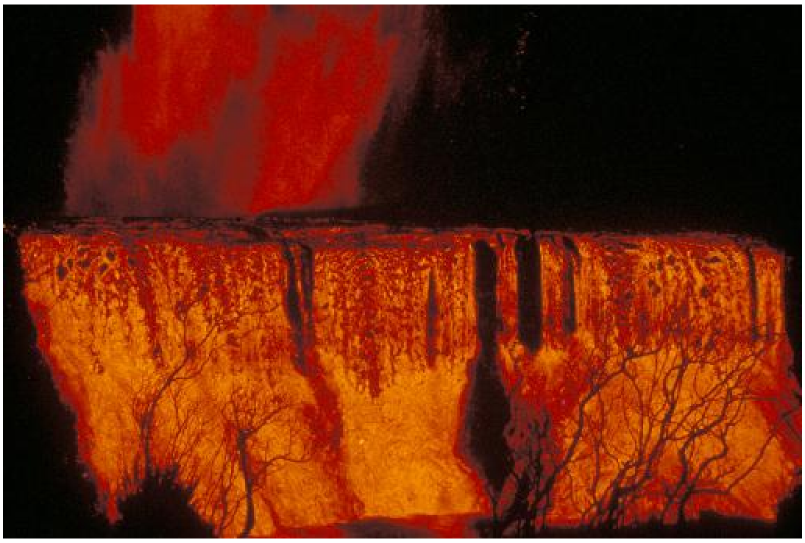


Figure 1.43: Basalt erupting from a fissure, with its low viscosity, running like water into a hollow.

gas are often trapped in basaltic lavas as they cool, and become preserved as spherical **vesicles**; there is an illustration of this in Figure 1.41. In very active volcanic areas, many sheets of basalt can be laid down in this way, as tabular basalts over wide areas. Some of these shrink as they cool, breaking into the vertical polygonal columns of **columnar basalt** (shown in Figure 1.44). If basalts are erupted under water, they are often extruded as thin tongues of lava that cool quickly into pillow-like shapes. Each pillow has a very fine-grained (chilled) edge, is slightly coarser inside, and also often contains vesicles. As the eruptions continue, the pillows build up, so a sequence of **pillow basalts** (shown in Figure 1.45) shows that the eruption must have happened underwater.

Intermediate magmas are more viscous than mafic ones. While they can flow out of central volcanic vents as thick andesite lavas, they often solidify in the vent. Pressure builds up on this volcanic plug and eventually the volcano erupts violently, often ejecting **volcanic blocks** and huge quantities of **volcanic ash** high into the air. These solid eruption products are called pyroclastics (*pyro* = fire-formed; *clastic* = broken material). The blocks and ash rain down on the surrounding area, often producing the typical cone-shape of many central vent volcanoes, as shown in the photograph in Figure 1.46. Andesitic volcanoes are much more dangerous than basaltic ones and some eruptions have killed thousands of people. To simulate magma viscosity, try the ‘See how they run: investigate why some lavas flow further and more quickly than others’ activity on the `http://www.earthlearningidea.com` website.

Silicic magmas are even more viscous than intermediate ones, which is why silicic lavas are rarely found. Instead, silicic volcanoes tend to have very violent eruptions, erupting enormous volumes of ash from central vents catastrophically (Figure 1.47).

Igneous magmas that don’t reach the surface often **intrude** through the rocks above as large upside-down raindrop shapes. These **intrusive** large drop-shapes, that can be

Figure 1.44: A basalt flow that cooled and fractured into vertical columnar basalt.

Figure 1.45: A basalt pillow lava exposed in a rock face.

Figure 1.46: A central vent volcano erupting intermediate magma violently as a billowing ash cloud.

Figure 1.47: Deposit of volcanic ash with small bombs in the upper layer.

tens of kilometres across, are called **plutons**. Since plutons cool slowly, their rocks are always coarse-grained. As they cool, the plutons heat up the surrounding rock, producing metamorphic zones that can be hundreds of metres wide, called **metamorphic aureoles**.

If the magma remains liquid, it can intrude higher into the crust, forcing its way through cracks in the rock and along bedding planes as sheets of magma. The cooling of this magma is much quicker, so the igneous rocks produced are normally medium-grained. The edges of these intrusions cool even faster, forming fine-grained **chilled margins** and heating the edges of the surrounding rock to form thin metamorphic zones called **baked margins**. The sheet-like igneous intrusions that cut across rocks are called **dykes** (Figure 1.48) whilst sheets along bedding planes are **sills**.

This range of igneous processes allows us to identify the igneous rocks and structures you might find in a rock face according to first principles. Plutons are deep slow-cooling intrusions which are often silicic (made of pale-coloured coarse-grained granite) or mafic (darker coloured coarse-grained gabbro). Dykes and sills are shallower tabular intrusions that are usually formed of medium-grained rocks. Mafic rocks that reach the surface in volcanic fissures produce tabular or pillow basalts. Intermediate magmas erupt from central vents forming andesitic lavas but also deposits of volcanic blocks and ash, whilst silicic magmas produce huge volumes of volcanic blocks and ash in highly explosive eruptions.

1.5 Metamorphic rocks - formed by heat and pressure in metamorphic processes

Metamorphic rocks have been changed from their original rocks by great heat and/or pressure deep in the Earth's crust, but have not been heated up enough to melt them (if they

Figure 1.48: Igneous dykes cutting through the surrounding rock and also cutting through each other.

had become molten, they would have formed igneous rocks). So metamorphism is defined as the recrystallisation of rocks by heat and/or pressure, without complete melting. Metamorphic recrystallisation forms new minerals and new rocks with different properties. The recrystallisation produces interlocking crystals, like those found in igneous rocks. Whilst igneous rocks have randomly orientated crystals, most metamorphic rocks have crystals that are aligned. Being formed of interlocking crystals, both igneous and metamorphic rocks are generally tough and impermeable, so that water drains off them unless there are cracks for the water to sink into. Because metamorphic rocks are 'waterproof' some have been used for roofing buildings in the past, like the slates excavated from the slate quarry shown in Figure 1.49.

Just two major factors affect the sorts of rocks produced by metamorphism: the composition of the original rock that they came from, and the amount of heat and pressure to which they have been subjected. However, there are two main sorts of metamorphism, the metamorphism caused by baking by hot igneous intrusions, and the metamorphism caused by great heat and pressure deep in the roots of mountains during **mountain-building episodes** (also called **tectonic** episodes, since the rocks are affected by tectonic activity). Metamorphism by baking is caused by igneous intrusions and is called **thermal metamorphism**, while metamorphism caused by both increased heat and pressure is much more widespread and is called **regional metamorphism**.

The common minerals that are most changed by metamorphism are the clay minerals found in mudstones and shales. As metamorphism increases, the clay minerals recrystallise into a range of new minerals, so the greatest variety of metamorphic rocks is

Figure 1.49: An old slate quarry, showing metamorphic slates without the bedding planes usually seen in sedimentary rocks. The slates were cut from the quarry benches seen in the photo.

caused by the metamorphism of fine-grained sedimentary rocks. Whilst the quartz and calcite common in sandstones and limestones are also affected by metamorphism, their composition doesn't change, although the crystals often recrystallise into different shapes.

When magma intrudes cracks and bedding planes in mudstones, it will cool down to form dykes and sills. As the magma cools, the mudstones at the edges of the intrusions are heated and thermally metamorphosed, forming a thin fringe of metamorphic rock, called a baked margin. With much bigger intrusions, like the plutons that can be several kilometres across, the 'baked margins' are much wider because the plutons originally contained much more heat and took much longer to cool. These 'baked margins', which can be tens or hundreds of metres across, are called metamorphic aureoles. As the mudstone is metamorphosed, the clay minerals recrystallise into new metamorphic minerals scattered through the rock with random orientation (Figure 1.50). If the dykes, sills or plutons have intruded limestone, the calcite crystals in the limestone will have recrystallised into a random texture of interlocking calcite crystals, forming the metamorphic rock, marble. Thin, baked margins of marble fringe dykes and sills, whilst much larger zones of marble are found in metamorphic aureoles. Similarly, when sandstones are intruded, the quartz crystals recrystallise into a tougher rock of interlocking grains, called **metaquartzite**. Thin metaquartzite bands fringe sheet intrusions and wider metaquartzite zones are found in metamorphic aureoles. We can easily distinguish marble from other types of metamorphic rock because, like the limestone it originally came from, it is composed of calcium carbonate that reacts to the one-drop acid (dilute HCl) test.

Figure 1.50: Mudstone metamorphosed in a metamorphic aureole, showing the new randomly orientated metamorphic minerals.

Rocks containing randomly orientated metamorphic minerals must have been produced by thermal metamorphism, but metamorphic rocks with aligned minerals are produced during regional metamorphism. Under the high temperatures and great pressures caused by tectonic episodes, when new minerals crystallise and original minerals recrystallise, they do so at right angles to the pressures affecting the rocks. So the new and recrystallised old minerals become lined up and parallel to each other. If the new minerals are flat platy minerals, as many new regional metamorphic minerals are, then the new rocks which form will develop a new metamorphic layering, called **foliation**.

When mudstone or shale are regionally metamorphosed, the clay minerals recrystallise into very fine grained new metamorphic minerals. The new rock develops a slaty foliation (cleavage) and is called **slate**, whilst any fossils in the original rock are either deformed or destroyed. Because of the alignment of the new minerals, slates can easily be split along the foliation, which is called **slaty cleavage** (Figure 1.51). This is why slates can be split into the thin waterproof sheets used to make roofs for buildings. Since the direction of the new slaty cleavage is often different from the direction of the original bedding in the sedimentary rocks, we can sometimes see both the bedding and the cleavage in slates, running in different directions (Figure 1.52). See how 'fossils' can be deformed by pressure using the `http://http://www.earthlearningidea.com` activity, 'Squeezed out of shape: detecting the distortion after rocks have been affected by Earth movements'.

Slate is a low-grade metamorphic rock, since it is formed at relatively low temperatures and pressures. As metamorphic pressures and temperatures increase, the new metamorphic minerals in the slates grow in size and some new minerals, like garnets, can form, producing a new coarser-foliated, medium-grade metamorphic rock, called **schist** (Figure 1.53). Continued metamorphism causes the minerals to separate into foliated bands pro-

Figure 1.51: Slate, a low-grade metamorphic rock, formed by the metamorphism of mudstone or shale. The new slaty cleavage can be seen in this photo.

ducing a high-grade metamorphic rock, called **gneiss** (Figure 1.54). Gneiss can also be formed by the high-grade metamorphism of granite.

When mudstones are regionally metamorphosed, the metamorphic sequence is from slate, to schist to gneiss. When limestones are regionally metamorphosed, marble is formed, as it is when limestones are thermally metamorphosed (Figure 1.55). In regionally metamorphosed marbles, the calcite crystals can be aligned, allowing them to be distinguished from marbles produced by thermal metamorphism. Similarly, regional metamorphism of pure sandstone forms metaquartzite that can have aligned grains, helping us to distinguish it from thermally-metamorphosed metaquartzite (Figure 1.56). You can simulate how metamorphic rocks are formed using the `http://http://www.earthlearningidea.com` activity, 'Metamorphism - that's Greek for 'change of shape', isn't it?: What changes can we expect when rocks are put under great pressure in the Earth?'.

Regionally metamorphosed areas are the roots of mountain chains that have become exposed by the erosion of the rocks above. You can trace the progression of metamorphism, if the margins of the region are composed of mudstones, limestones and sandstones, containing fossils. Moving inward, broad regions of slate are found, sometimes with deformed fossils. These are followed by schist zones, where any fossils have been destroyed, and finally zones of gneiss. Meanwhile, limestones become marbles, progressively destroying fossils, while sandstones become metaquartzites. So as you move in from the margins, original structures and fossils are progressively lost, the crystal size of the minerals becomes larger, and the rocks tend to become more compact and tougher.

Figure 1.52: Bedding and cleavage seen in slate, formed from mudstone by regional metamorphism. The bedding runs steeply from the lower right to the upper left and is shown by the different bands of colour. The cleavage is the series of cracks that slope up gently from right to left. The tectonic forces that caused the metamorphism were at right angles to the cleavage, from top to bottom of the photo.

1.6 Deformation in rocks - geological structures

Rocks in the Earth's crust can be put under pressure by three different sets of forces: they can be compressed by compressional stresses; they can be pulled apart by tensional stresses; or they can, under pressure, slide past one another due to shear stresses. There is a fourth type of stress, caused by turning forces, but these are not geologically very common.

Not only do three types of stress commonly affect crustal rocks, but rocks respond in three different ways. The rock can absorb the stress, like a rubber ball, but when the stress is removed, it bounces back. This is called **elastic behaviour** and, although as we shall see, this is important in earthquakes, the effects cannot be seen in rocks, since they have sprung back elastically to their original shape and size. The rocks may bend and flow, like clay does when you mould it with your hands. This is **ductile behaviour**, the rocks remain distorted into folds that can be seen clearly. Finally the rocks may break; this is **brittle behaviour** and results in different forms of rock fracture.

Whether a rock bends, breaks or behaves elastically under stress depends on a range of different factors, including what the rocks are made of, how great the stress is, the temperature of the rocks, how deeply buried they are, and for how long the stresses are applied. The result is that the same rock can behave differently at different times and under different conditions and can show the effects of both ductile and brittle behaviour; so folded rocks can be fractured as well.

Figure 1.53: Schist, a medium-grade metamorphic rock, formed by the continued metamorphism of slate, by higher temperatures and pressures. The foliation gives this flat surface of aligned platy minerals.

Figure 1.54: Gneiss, a high-grade metamorphic rock, formed by the continued metamorphism of schist by even higher temperatures and pressures, or by the high-grade metamorphism of granite. The high pressures deformed the bands of gneiss into tight folds before this rock was intruded by a narrow dyke.

Figure 1.55: Marble, produced by the metamorphism of limestone either by high temperatures in thermal metamorphism, or by high temperatures and pressures in regional metamorphism. This specimen clearly shows the interlocking crystal texture.

Figure 1.56: Metaquartzite, produced by the metamorphism of pure quartz sandstone, by either thermal metamorphism or regional metamorphism. This photo shows the interlocking quartz grain texture that makes it such a tough rock.

So we have three types of stress and three types of behaviour, and you might anticipate seeing the results in rocks in nine different ways. However, as we don't see the effects of elastic behaviour, this cuts this number down to six. When rocks are pulled apart by tensional stresses and flow, the main effect is that the layers become thinner and it is usually impossible to tell that this has happened. We rarely see the ductile effect of shear stresses in rocks either, so we are left with only four common effects to examine below.

When rock sequences are strongly compressed and flow, we see the effects as **folding** of the layers. The rocks may be deformed into gentle open folds or into a series of tight folds. The place where the rock has bent most is called the **fold axis**. Since there is never just one layer that is bent, but many, if you join the axes of all the folded layers together, a plane is formed and this is called the **axial plane surface**. Compressional stresses always act at right angles to the fold axial plane surfaces, so we can use the shape of the folds to work out the directions of the stresses that deformed them. The directions of axial planes are measured as compass directions; folds with north/south axial planes must have been formed by east/west stresses.

Where rocks are folded, you often can't see the folds themselves, you just see the sides or **limbs** of the fold, as layers that were once horizontal but are now sloping. The direction of downward slope is called the **dip** and can be measured as an angle to the horizontal. At right angles to the dip direction is the **strike**, which is measured with a compass. So rocks that dip towards the east have a north/south strike, which is parallel to the directions of the fold axial plane surface. This may sound complicated but you can make a simple model to explain it by using your hands. Put the sides of your hands, with the little fingers together, into a downfold, with both hands sloping at the same angle. The fold

Figure 1.57: Folded rocks, with a downfolded syncline to the left and an upfolded anticline to the right. The axial plane surfaces of these folds go into and out of the cliff face and the compressional stresses that deformed them came from the left and right. These are tight folds and you can see their scale from the street light in front of them.

axial plane surface is vertical and runs through the join between your hands. Each hand forms the limb of the fold and dips towards the centre. The strike direction is parallel to your fingers and to the fold axial plane surface.

If rocks in a cliff face are dipping towards the left and you followed them to the left far enough, you would find them bending up again. The rocks are therefore forming a downfold, this is called a **syncline**. Similarly, if you followed the dipping rocks to the right far enough, you would eventually find them bending down again. Upfolds like this are called **anticlines**. So dipping rocks are just the visible parts of much larger folds that become synclines in one direction and anticlines in the other.

You can use these principles on any dipping rocks to work out where the synclinal and anticlinal axial planes are. For example, in Figure 1.57, the synclinal axial plane surface must be to the left and the anticline to the right. You can also work out the directions of the stresses that caused this tilting; here, they must also have come from the left and right. So, you should now be able to use these principles on any tilted or folded rocks you find, to work out the directions of the stresses that caused them. Since folds are three dimensional, you can not only see them in vertical cliff faces but also on horizontal surfaces too, as in the aerial view in Figure 1.58. The same principles are used to work out the stress directions wherever you see folded or tilted rocks. Folding results in **crustal shortening**, where the crustal rocks have been compressed and take up less space than they used to.

When rocks are compressed and fracture, compressional **faulting** occurs as one slab of rock slides up over the other, again resulting in crustal shortening. The sliding surface is called the **fault plane** and fault planes in compressional faults usually dip at around

Figure 1.58: A region of folded rocks seen from the air. An anticline makes the ridge in the distance and there is a syncline in the left foreground. The fold axial plane surfaces run up and down the photo and the compressional stresses came from left and right.

45°(between 30 and 60°). These faults, shown in Figure 1.59, are called **reverse faults** (because they have moved in an opposite direction to the more common 'normal' faults, described below). When compressional forces are very great, slabs of rock can be forced great distances over the rocks beneath, when the sliding surface usually has a much lower slope of 10°or less. These types of reverse faults are called **thrust faults** (Figure 1.60), and sometimes rock can be moved tens of kilometres along them. You can make your own folds and compressive faults using sand and flour in a small plastic box using the 'Himalayas in 30 seconds!' activity on the `http://www.earthlearningidea.com` website.

When rocks are pulled apart by tensional stresses, they can fracture to form **normal faults**. They are called normal faults because they are the most commonly seen types of faulting (Figure 1.61). The rocks fracture, usually along a steep fault plane of 60°or more, and the rocks on one side slide down relative to the rocks on the other. The tension was at right angles to the fault plane and the result is **crustal extension**, with the rocks taking up more space than they did originally. Try making tensional faults in a box using the `http://http://www.earthlearningidea.com`, 'A valley in 30 seconds' activity.

Shear stresses cause slabs of rock to move sideways across the Earth in relation to the rocks on the other side. These are called **strike-slip faults** because rocks striking across the land surface have slipped sideways relative to the rocks on the other side (Figure 1.62). The fault planes of strike-slip faults are usually vertical. These result in neither crustal shortening nor crustal extension and are most easily seen by viewing rock sequences from above.

Where you can see layers on each side of a fault that used to match up, but are now broken, it is easy to tell there is a fault there and to work out which type of fault it is and how far the rocks have been moved (the **fault displacement**). However, if you can't see

Figure 1.59: Reverse faults. The compressional stresses came from left and right in this photo, and the rocks on the left were moved up over the rocks to the right.

Figure 1.60: A thrust fault. You can tell that the rock sequence at the top has been thrust over the rocks at the bottom from the left to the right because the lower rocks have been bent into a drag fold as the upper rocks were forced over them.

Figure 1.61: A normal fault. This steep fault was caused as the rocks were pulled apart by tension to left and right, allowing the rocks on the right to slide down relative to the rocks on the left.

Figure 1.62: A strike-slip fault. The strike of the rocks is from lower left to upper right. Along the fault, the rocks in the background have been moved to the right relative to those in the foreground.

Figure 1.63: The rocks of this quarry wall have horizontal bedding planes and at least two sets of vertical joints.

layers that have been dislocated, it is much harder to tell the type of the fault and work out the amount of fault displacement. In rocks that have no layers, you may not be able to tell there is a fault there at all, you might just see a fracture and not know that there had been fault movement along it. If this is the case, you have to look for other clues of fault movement, such as bits of fractured rock along the fault plane (**fault breccia**).

Faults are defined as fractures with movement of the rocks on either side. Rocks can have other sorts of fractures too and the most common of these is **joints**. Joints are straight fractures where the rock has not moved up, down or sideways on either side, and are usually caused when an area of the crust has been put under pressure and later the pressure is released. Most joints are vertical or near-vertical and form parallel sets. If, at different times in the past, the crust has been put under pressure from different directions, then two or more joint sets can be formed, running in different directions, which break the rocks up into large blocks. Joints are important: not only are they the most common fractures seen in rocks, but they are also pathways for underground fluids. They control the ways in which rocks break in quarries and mines as well, which is why they were first called joints, looking as they do like the joints in a cut stone wall (as shown in Figure 1.63). Minerals may have crystallised from fluids flowing along joints in the past, to form mineral veins. Joints are also formed as igneous rocks cool and contract; many of the joints in plutons probably formed in this way, as did the columnar joints in basalts.

A structural feature that tells you a lot about the geological history of an area is an **unconformity**. Unconformities form when a rock sequence has been buried and hardened into rock. If it is then uplifted and the rocks above are eroded away, a surface is eroded across the rocks, called an unconformity surface, as shown in Figure 1.64. Later, another

Figure 1.64: An unconformity. Older rocks beneath are overlain by much younger rocks above.

sequence of sediments is deposited on this surface and becomes hardened into rocks. Unconformities are most easy to see when the older rocks beneath the unconformity have been folded or tilted, and so have a different angle of dip from those above; these are called **angular unconformities**. Unconformities tell us a tale: the first formed rocks were buried, became hard and then were uplifted by a mountain-building episode. Over millions of years the rocks above were eroded and an erosion surface was cut across them, like the near-horizontal surfaces found on rocky coastal foreshores today. Later, a sequence of sediments was deposited on top of this surface and it too became buried, hardened and possibly tilted. Finally, the whole sequence was uplifted again and the rocks above eroded away to allow you to see the unconformity as it is today.

1.7 Rock exposures contain evidence of the sequence of geological events that formed and deformed them

Rocks can tell us the tales of how they formed and were changed if we apply a series of principles to them, as for the unconformity story above. These are called ‘Principles’ if they generally apply, but there can be certain unusual circumstances in which they don’t. If they always apply, we call them ‘Laws’ instead. Many of them have very complex-sounding names, but the ideas are very simple.

We understand how many surface rocks and fossils formed by applying the ‘Principle of

Uniformitarianism' that the 'present is the key to the past'. Most of the different types of sediment and volcanic rock we find in the rock record are being formed on Earth today, so we can investigate modern Earth processes to get good insights into how they were originally formed. Similarly, many fossils have modern living relatives today, so we can examine these to find out how the fossil organisms probably lived and died. It is more difficult to determine how extinct organisms lived and how rock-forming processes worked that don't seem to be happening on the planet today, but even for these, the 'Principle of Uniformitarianism' can give us clues if we examine similar organisms and processes.

The five principles below are called '**Stratigraphic Principles**' since they apply to **strata**, or sedimentary and volcanic layers. Two of these are the '**Principle of Original Horizontality**' and the '**Principle of Lateral Continuity**'. 'Original Horizontality' states that most sedimentary and volcanic rocks were originally laid down in near-horizontal layers. This means that if we find them in layers that are not horizontal, they must have been tilted by tectonic activity. There are unusual instances when sediments and volcanic layers are not deposited flat, as in current bedding and dune bedding, or the layers in scree slopes or on the sides of volcanoes, which is why 'Original Horizontality' is a principle and not a law. 'Lateral Continuity' states that sedimentary and volcanic rocks once formed laterally continuous layers over wide areas. We know that they cannot have been laterally continuous over the whole Earth, since they must either have hit the edge of the area where they were deposited or died out laterally, so this too is a principle and not a law.

The next principles are vital in sequencing rock events. The '**Principle of Superposition of Strata**' states that the rocks on top are the youngest. This is because rocks are deposited in layers that build up over time, so the oldest is at the bottom and the youngest at the top. Since it is possible for such sequences to be turned over by intense folding or for older rocks to be thrust over younger ones by intense compression causing thrust faulting, 'Superposition of Strata' remains a principle and not a law. The '**Law of Cross-Cutting Relationships**' states that anything that cuts across anything else must be younger. The 'anything' can include faults, joints, dykes, plutons and unconformity surfaces. This law applies in all circumstances and to all rocks, since something cannot be cut until it is first formed. However, sometimes you have to examine the evidence very carefully to be sure that something is indeed cutting something else, and it doesn't just look that way. The '**Law of Included Fragments**' states that anything included in a rock must be older than the rock that includes it. Included fragments are such things as the pebbles found in conglomerates and the pieces of surrounding rock called xenoliths, sometimes included in plutonic igneous rocks. This is a law since, for anything to be included, it must be older, but sometimes you have to examine the evidence very carefully to be sure. See for yourself how these stratigraphic principles work, by trying the `http://www.earthlearningidea.com` activity, 'Laying down the principles'.

The '**Law of Faunal Succession**' applies to fossils, and so is not a stratigraphic principle, in spite of the fact that it is used to sequence strata. It states that groups of fossil animals follow one another in time in a predictable sequence and we now know that plant fossils can be used in the same way. It was by using the 'Law of Faunal Succession' that geologists were first able to sequence rocks, divide up the geological time scale and make the first proper geological maps. Fossils have now been sequenced all over the world to provide very detailed evidence for the relative ages of rocks. When fossils appear at the same time in rocks across the world, we can use these fossils to say that the rocks must have been formed at the same time too. This method of identifying rocks of the same age in different areas is called **correlation** and rock correlation using fossils has been essential in linking together the geological sequences of different areas, regions, continents and across the world. We now know that the reason for the 'Law of Faunal Succession', that fossils are always found in the same sequence across the world, is evolution.

A huge range of fossils can be found in rocks, but only a few of these can be used for correlation. The best fossils for correlation have these key features:

- they were common, so many of them could be fossilised;
- they were easily preserved, usually because they had hard parts, and so are frequently found;
- the fossil group evolved quickly over time, meaning that the fossils in different beds are slightly different;
- they were widespread, so are found in many rocks across the world;
- they are found in many different rock types, such as sandstones, limestones and shales;
- and they can be easily identified, at least by experts.

Two types of fossil that fit these requirements are graptolites and cephalopods.

Graptolites are now extinct, so it is difficult for us to know how they lived. However, this doesn't matter if we are just using them for correlation. They were small colonies of animals that were strung together in saw-blade-like shapes. Each animal lived in a small living chamber called a **theca** and the string of animals is called a **stipe** (see Figure 1.65). Their important properties are:

- they were very common in ancient seas;
- they were made of a hard organic material that readily fossilised;
- they evolved quickly over time, so have many different forms, in particular the shapes of the stipes changed, as you can see in Figure 1.66, and the shapes of the thecae were also very varied;
- they lived right across the world's oceans;
- as they floated in the sea, they could be found in sandy, muddy and limestone environments, and so are preserved in different rock types;
- experts can easily identify them from their stipe orientations and the shapes of their thecae.

Figure 1.65: Graptolites. The largest fossil here had four stipes and the small thecae or living chambers can be seen along each stipe.

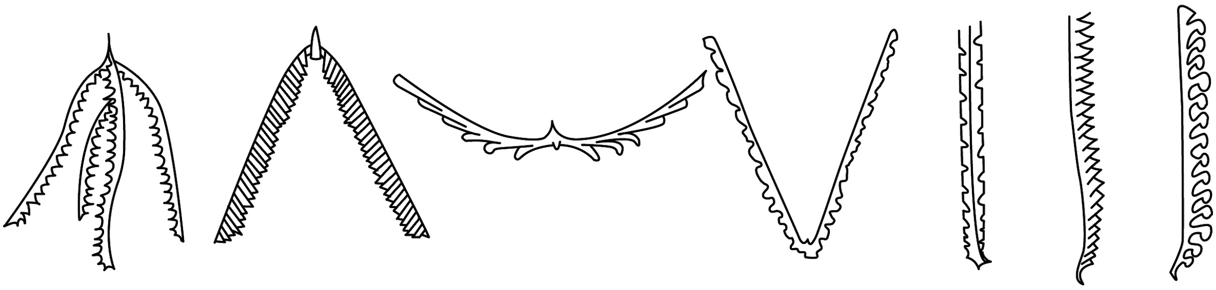


Figure 1.66: How graptolites evolved, from the four-stiped form common around 480 million years ago on the left to the single-stiped form common around 420 million years ago on the right.

Cephalopods are not extinct, but the sorts with coiled shells that are useful in correlation, nearly became extinct and only one type can be found alive today (it is shown in Figure 1.67). Nevertheless, we know from these living animals that they lived in the sea, floating in the water, and could move around by squirting jets of water backwards. The animal living in the coiled shell had tentacles, like an octopus, that could grab passing small animals for food. When they were attacked they could withdraw into their shells for protection. Inside the coiled shells there were chambers of gas that helped the animal to float in the water. Where the chamber walls joined the outside of the shell they formed a line, called a **suture line**. You can see these if you peel away the outer shell, exposing the chambers and chamber walls beneath (as has been done in Figure 1.68). In the earliest shelled cephalopods, the chamber walls were straight lines, but as the animals evolved, the lines became more and more complex, and it is these complex suture lines that help us to identify the different types. The cephalopods with the most complex suture lines, that lived between about 200 and 65 million years ago, are called ammonites (Figure 1.69).

Shelled-cephalopods have all the properties that make them excellent fossils for correlation:

- like graptolites, they also were very common in ancient seas;
- their hard shells were easily fossilised;
- their suture lines evolved quickly, and three of the main shapes are shown in Figure 1.70;
- they lived in all seas and oceans;
- since they floated in the sea, and continued floating even after they died, their shells can be found in all sorts in environments and sediments;
- experts can easily identify them from their suture lines.

With all these properties, it is not surprising that cephalopods have been key fossils in helping us to unravel the geological history of the Earth.

A final rule that helps us to work out geological histories of rock sequences is the fact that rocks cannot be deformed or metamorphosed until they have first been formed. So we now have all the principles and laws needed for working out how rocks were first formed and the sequence of changes that happened to them after formation. When all the changes have been put into order, the geological history of the rock sequence has been explained.

These methods were used to work out the geological time sequence of all rocks on Earth, as shown in Figure 1.71. This is the international geological time scale. The principles above only help us to put things into order, to work out the **relative ages** of the events, but they do not tell us how old the rocks and events are. To do this, we need another technique that will give us the **absolute ages** of the rocks.

Geologists have been able to work out the relative ages of rocks and events for more than 200 years, but an absolute dating technique has only been widely available for about 50 years. This is **radiometric dating** and is based on the fact that radioactive atoms decay

Figure 1.67: A shelled cephalopod.

Figure 1.68: A shelled cephalopod fossil with the outer shell removed so that the chambers and the suture lines can be seen. The suture lines here have fairly simple shapes, so this must be a goniatite.

Figure 1.69: A coiled cephalopod fossil with the outer shell removed to show very complex suture lines. Complex sutures like these show it must be an ammonite.

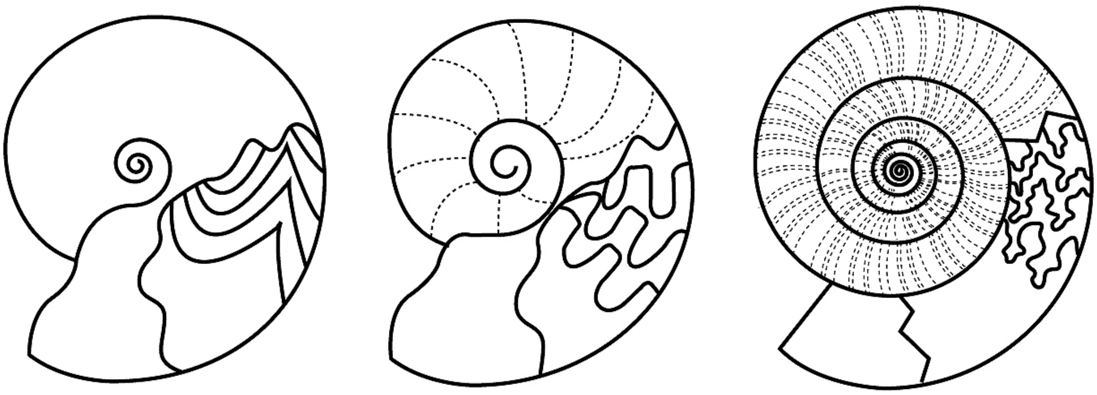


Figure 1.70: The change of ammonoid suture lines over time, from the simple sutures of goniatites, common around 350 million years ago in the left hand diagram, to the more complex sutures of ceratites, common around 240 million years ago in the centre to the very complex sutures of ammonites, found in 190 million year old rocks in the right hand diagram. Ribs on the outsides of the fossils are shown as dashed lines.

at fixed rates over time. So, if we can find a rock or mineral that contains radioactive atoms, and we can find out what proportion of them has decayed, and we also know the rate of decay, we can work out the age of the rock. For example, potassium (with the chemical symbol, K) has a radioactive component and is commonly found in igneous rocks like granite. When the granite first forms, the potassium-containing minerals contain only potassium. But the radioactive part of potassium decays to argon (Ar) over time. So, if we measure the amount of potassium that should have been in the rock, and the amount of argon it now contains, we can work out the age of the rock. Half the radioactive potassium would decay to argon in 1260 million years, so an igneous rock with half radioactive potassium/half argon must have crystallised 1260 million years ago.

Unfortunately we can only apply this method to igneous rocks and some metamorphic rocks that contain potassium (and the unusual sedimentary rock, greensand). This is true of other radiometric methods as well - we can only apply them to certain sorts of rocks. This means, for example, that we usually can't find the absolute ages of sedimentary rocks and fossils directly. If a bed of sedimentary rock containing a useful correlation fossil happened to have a lava flow below and above it, and we could work out the radiometric ages of the lava flows, we would have a good idea of the absolute age of the rock and its fossil. However, this is very unusual and, even when it does happen, the ages of the lava flows may be several million years apart, so that we can only find the approximate age of the rock and fossil.

Nevertheless, geologists have been working on this problem for many years, and now have a good idea of the ages of key correlation fossils and the rocks in which they are found. These ages have been added to the international geological time scale, so as well as knowing the sequence of global geological events, we also know when in the geological past they actually happened (Figure 1.71).

You can try the rock sequencing principles yourself through the http://www.earthlearningidea.com activity, ‘What is the geological history?’. Even better, try them on a nearby rock exposure in a cliff or a quarry instead.

Eon	**Era**	**System**	**Age, millions of years ago (Ma)**
			0
Phanerozoic	Cenozoic	Neogene	23
		Paleogene	65
	Mesozoic	Cretaceous	146
		Jurassic	200
		Triassic	251
	Palaeozoic	Permian	299
		Carboniferous	359
		Devonian	416
		Silurian	444
		Ordovician	488
		Cambrian	542
Precambrian	Proterozoic		2,500
	Archaean		3,800
	Hadean		4,600

Figure 1.71: The geological time scale, used internationally

Chapter 2

Reading landscapes: how landscapes contain evidence of the relationship between past and present processes and the underlying geology

2.1 The landscape is subject to processes of weathering, erosion and transportation

All the lumps and bumps you can see in the landscape, all the hills, valleys, ridges, mountains, lowlands, bays and headlands, are caused by just three things: the character and structure of the underlying rocks, the type and power of the surface processes and, nowadays, human activity. This chapter will help you to stand on a hill and make sense of all the lumps and bumps in the landscape that you can see.

In Figure 2.1 tough rocks form the hill the photo is taken from, the ridge in the distance and the hills in the background, while weaker rocks underlie the plain below. The plain is flat because the weaker rocks underlying it were eroded to a lower level before flat-lying sediment was deposited on the top. Human activity has modified all this by building roads and buildings and excavating quarries, and by agricultural activity over thousands of years.

Weathering and erosion remove material from the higher places on Earth and it is transported, largely downhill, to the lower parts, where it is deposited. So higher points become worn down and sediment builds up in the lower parts. Weathering, erosion, transportation and deposition are therefore key elements of the sedimentary cycle.

Weathering attacks all natural rock surfaces as well as all constructions, such as buildings, bridges and dams. **Weathering** is defined as: ‘the natural break up and break down of rock and other materials at the Earth’s surface, without the removal of solid material’. ‘Break up’ means that the material is broken into smaller pieces by physical processes, whilst ‘break down’ is chemical breakdown, into new compounds. During weathering,

Figure 2.1: Natural lumps and bumps in the landscape, caused by the effects of underlying rocks of different toughness and a range of natural surface processes. A view from Glastonbury Tor across the Somerset Levels in South West England.

Figure 2.2: Freeze-thaw weathering has forced the cracks in this rock apart.

material can be dissolved and removed in solution, but any movement away of solid material is erosion and not weathering. Weathering happens in place (*in situ*) and loosens material that is later removed by erosion.

So, **physical weathering** causes the break up of rock surfaces, and the most common type of physical weathering in areas where the weather becomes cold enough to freeze, is **freeze-thaw weathering** (Figure 2.2). Water is a very unusual substance because when it becomes solid, its volume increases (usually when liquids become solid, their volumes decrease). When water freezes, the volume of the ice formed is 9% more than the volume of the original water. This means when water gets into permeable rocks, between the grains or along cracks, and freezes, it expands and pushes the grains and cracks apart. When it melts, a little more water fills the space and later freezes again. Many cycles like this eventually weaken the rock so that pieces break away, so it has most effect where there is frequent freezing and thawing, as on many mountain tops. After being loosened, the broken pieces are moved by erosion, often by gravity, causing them to fall away. So beneath rock faces affected by freeze-thaw weathering, gravity-erosion has usually built up a sloping pile of angular rock fragments, called **scree** (see Figure 2.3). You can see the effects of freeze-thaw weathering on the outsides of walls and buildings as well, with fragments of brick, stone and concrete building up at the bottom of the wall.

Physical weathering also affects rocks in desert areas, because they become very hot in the day and very cold at night (see Figure 2.4). Since different minerals in the rocks expand and contract at different rates, the rock is weakened. This is weathering by heating and cooling, and commonly affects granites, where curved sheets can be broken away in a process called **exfoliation**. Lab experiments show that this doesn't happen to completely dry rocks though, so there must be a little water present (often from dew in deserts), causing some chemical weathering that weakens the rock as well.

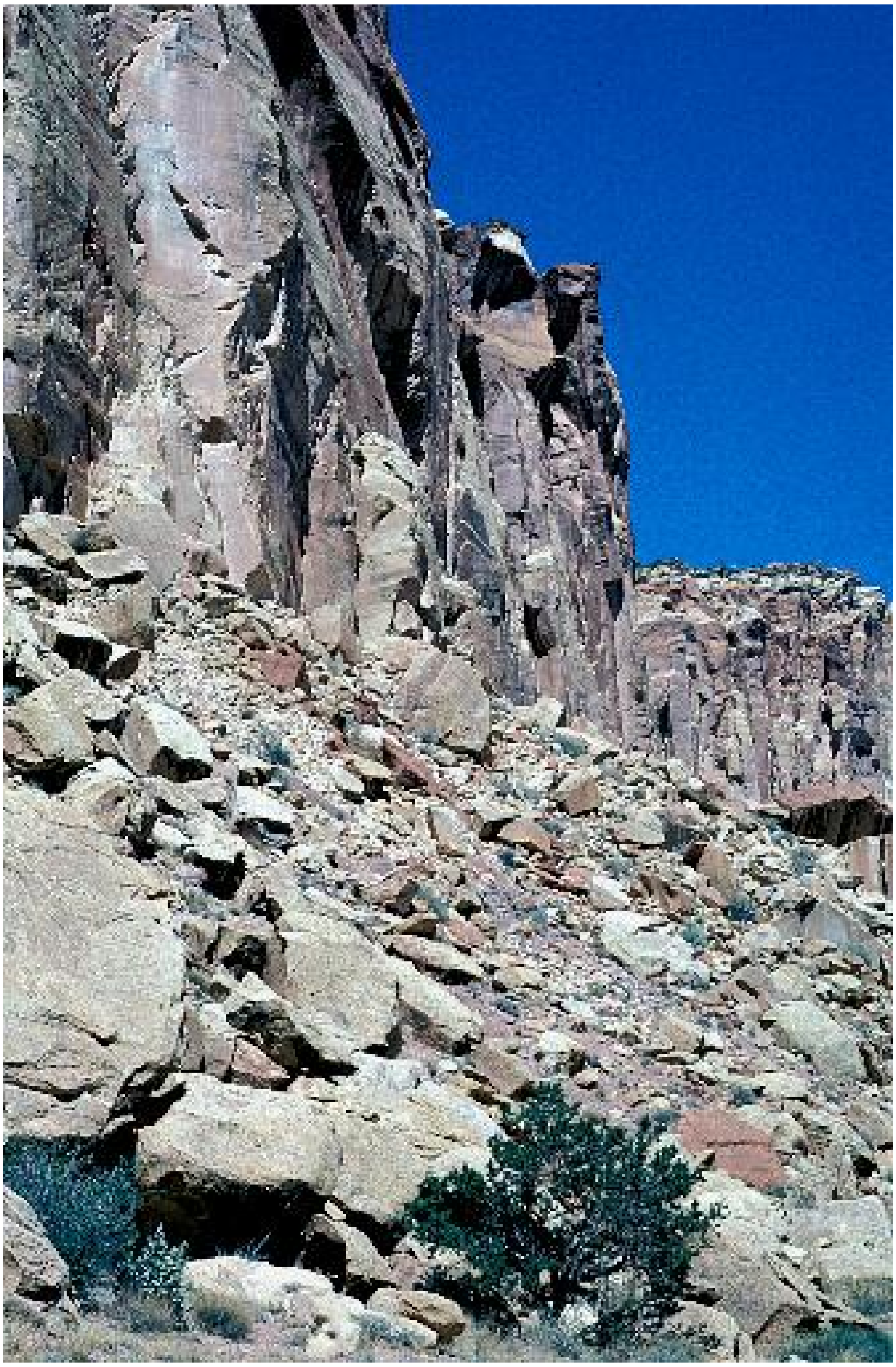


Figure 2.3: Rock fragments loosened by freeze-thaw weathering have been eroded by gravity, falling to make a sloping heap of scree under the rock face.

Figure 2.4: Granite affected by heating and cooling in a desert area. Curved sheets have been broken away in exfoliation.

Figure 2.5: Discolouration caused by chemical weathering along the joints in fine-grained sandstone.

Chemical weathering attacks rocks where the rain and soil water contain acid. Natural rainwater contains some dissolved carbon dioxide (CO_2). Soil also contains carbon dioxide, produced by all the small animals that live there. When rainwater flows through soil, it dissolves even more carbon dioxide, forming carbonic acid. In polluted areas, rainwater can contain other acids as well; it is then called '**acid rain**'. Acid rain contains dissolved nitrogen compounds forming nitric acid and dissolved sulfur compounds producing sulfuric acid as well as carbonic acid. You can tell when rocks and building materials have been attacked by acid chemical weathering, because the new compounds formed by chemical breakdown are usually of different colours. Any discolouration of rock or building stone surfaces is usually the result of chemical weathering. When the new compounds produced by chemical weathering are carried away in solution, this is part of the weathering process. But when chemical weathering loosens solid material and this is later moved, the movement of the solid materials is erosion. Limestone is strongly attacked by chemical weathering because naturally acid rainwater and acid rain both contain acid that directly attacks the calcium carbonate minerals in the limestone. The one-drop acid test for limestone shows this effect by the fizzing caused by the chemical reaction. Since the solid limestone is removed in solution, this is weathering, involving no erosion.

Chemical weathering is most active in tropical regions where temperatures are high (speeding up chemical reaction) and where there is often abundant water from rainfall. Weathering rates are increased where water can penetrate cracks in rock. Sandstones and igneous rocks often become discoloured along joints (see Figure 2.5). Meanwhile in limestone areas, joints are widened by chemical weathering so that limestone blocks become separated by wide cracks at the surface, as shown in Figure 2.6.

Plants have both physical and chemical weathering effects; together these effects can be called **biological weathering**. Plant roots and rootlets penetrate cracks in the rock and can grow along the edges of grains, forcing them apart. Meanwhile the rootlets release organic acids that chemically attack the rock. Fragments of rock become loosened and new compounds are carried away in solution. A progression of biological effects on

Figure 2.6: The joints in this limestone pavement have been widened by chemical weathering.

Figure 2.7: Lichen growing on a rock surface, with the physical and chemical effects of biological weathering breaking the rock surface down.

rocks can be seen, starting with lichen growing on bare rock surfaces (see Figure 2.7). The material loosened by the lichen growth is colonised by moss, which breaks down the material further. Then other plants, worms and other small animals, colonise this new soil, causing more biochemical effects and a thicker soil develops. Thus, the soil which covers much of our planet and is so important for growing the crops that feed us all, is produced by biological weathering processes. Use the 'Weathering - rocks breaking up and breaking down' activity on the `http://www.earthlearningidea.com` to match pictures of weathering to the processes that formed them, and see how Darwin 'discovered' how soil formed in 'Darwin's 'big soil idea''.

Erosion is: 'the removal of solid material, which has often been loosened by weathering'. Four main agents remove sediment: gravity, flowing water, wind, and ice. Each of these produces sediment which contains clues that tell us how it was transported and deposited, and we can recognise these clues in sediments preserved in the rock record.

If a piece of the roof above you falls down, it has been removed by erosion by gravity. It will be transported by gravity through the air and then be deposited on your head. In a similar way, the rock fragments in Figure 2.3, having been loosened by weathering, fell off and were deposited in the slope of scree under the rock face. Scree deposits are sloping heaps of angular pieces of rock, ranging in size from boulders to mud-grade sediment. They are typical of the poorly-sorted sediments found near their source rock.

Loose material is moved further downhill, either by gravity in landslips, or by being washed down by water. It eventually reaches gullies, streams and rivers, where it is transported by water currents. The sediment is moved by sliding or rolling along the bed, a process called **traction**, or by bouncing along, **saltation**, or is carried along buoyed up by the water current, in **suspension**. Dissolved material is also carried in **solution**. As sediment

Figure 2.8: This river has sorted the sediment into separate areas of gravel and sand and is carrying the mud out of the area.

Figure 2.9: A wind storm, transporting sand and carrying finer sediment out of the region.

particles are carried along, they are rounded and ground down, producing fine-grained sediment. The grinding down or abrasion of pebbles as they are rubbed together is called attrition, and they also grind down and abrade the bedrock they move over. Meanwhile, the water currents sort the sediment into gravels, sands and muds, which are deposited in different areas of the river valley, as shown in Figure 2.8. River sediments are therefore better sorted and more rounded than scree deposits. When they reach the sea, waves and tidal currents abrade and sort the sediments even more, into rounded beach gravels, well-sorted beach and shallow sea sands, and mud deposited in tidal mud flats. So, the more rounded the gravels, the longer the time and distance of their transportation. The level of energy of the water that deposited the sediments can be gauged from their size, since fast-flowing, high-energy currents are needed to carry pebbles, whilst sands are carried and deposited by slower currents. Muds and clays are only deposited by settling out of suspension in quiet conditions. So, the finer the sediment, the lower the energy of the water when the sediment was deposited.

Winds erode and transport sand and mud-grade sediment, as in Figure 2.9. As in water, sand grains are rolled or slid along by traction or bounced along in saltation. The sands are usually deposited in dunes of well-sorted, rounded sand grains. Muds are blown in suspension in the air beyond the area and may eventually be deposited in the sea, where they settle out as deep-sea muds.

Ice erodes sediment by pulling off fragments of bedrock, but mainly by grinding rock fragments across the bedrock surface. The abrasion of the rock surface, and attrition of the rock fragments, produces more sediment, mostly fine-grained clay. All this is carried by the ice, without any sorting or rounding. When the ice melts, the sediment is dumped as heaps of debris (Figure 2.10) that is mainly clay with sand and some boulders, called **till**.

Clearly, the shape and sorting of the sediments deposited by each of the surface processes provide clues to the processes that transported and deposited them.

Figure 2.10: The mixture of boulders and clay transported and deposited by a melting glacier.

2.2 Valley shapes generally reflect the mode of their formation

In upland areas, valleys tend to be steep-sided because active erosion is cutting down into the surrounding hills and upland areas. Where rivers are cutting valleys, the sides normally have even slopes, giving the valleys V-shapes. This is because the river cuts down into the valley floor whilst material slumps and slides down the valley sides, keeping the V-shape. In areas where the rocks are very strong, the sides can be near-vertical, and the result is a gorge. You can see the sloping valley sides of the river in Figure 2.8 and even more clearly in Figure 2.11, where the valley has a typical upland river valley V-shape.

Some upland valleys have wide U-shapes since they were carved by glaciers. During the ice age, glaciers flowed down old river valleys, grinding away not only the valley floor, but also the valley walls. This abrasion of the rock surface on both the bottom and sides of the valley produced the typical U-shape you can see in 2.12. So U-shaped valleys are typical of areas that were originally glaciated.

Usually valleys in upland areas are guided by the underlying geology, with the rivers cutting through areas of weaker rocks, such as mudstones or shales, or following other weaknesses in the rock, like faults or joint patterns. Sometimes though, the river pattern seems to have no link to the underlying geology at all, when the drainage pattern is described as **discordant**. This is usually because the rocks you can see today were

Figure 2.11: A V-shaped valley, cut by a river in an upland area.

Figure 2.12: A U-shaped valley, cut through this mountainous area by a glacier during the ice age.

Figure 2.13: A meandering river channel, cut across broad flat valley floor sediments in a lowland area.

Figure 2.14: This plateau is formed of tough, flat-lying lava flows. The rocks of the lowland below were much less resistant to erosion.

originally covered by another set of rocks, and the river developed its pattern on these overlying rocks. Now that it has cut down through the overlying rocks and removed them, the pattern has become superimposed on the geology beneath, with rivers cutting across ridges and other upland areas for no clear geological reason.

The valleys seen in lowland areas are rather different. Here the main process is not erosion, but deposition, and rivers deposit sediment, filling up old valleys rather than eroding new ones. So lowland valleys tend to be broad with flat floors. Sediments are deposited across these flat-bottomed valleys during floods, so that the valley floors gradually build up over time. Between floods, the rivers cut their channels across the flat valley-floor sediments, often in winding meandering patterns (Figure 2.13). So a meandering river pattern is a sign that deposition is the main process active there.

So, the shapes of valleys can give clues to the underlying geology and the processes that are forming them. Similarly the shapes of hills can often tell us about the underlying geological pattern as well.

2.3 Landforms often reflect underlying geological structure

When sedimentary sequences have tough layers with weaker rocks between them, several typical landscape features appear, depending on how steeply the rocks dip. Tough rocks stand out as higher land and weaker rocks have been eroded away to make valleys and lowlands.

If the rock sequence is horizontal, the tough rocks form horizontal upland areas called **plateaus**. Tough sandstones and limestones often form plateaus, but plateaus are also commonly formed by widespread lava flows of basalt, since the basalt lavas are usually more resistant to erosion than the surrounding rocks (Figure 2.14).

If the sequence of alternating tough rocks and weaker rocks is dipping at a small angle (usually less than 10°), ridges develop that slope gently downwards in the direction of dip, but are steeper in the other direction. These asymmetrical ridges are called **cuestas** (Figure 2.15). Where there are several tough beds in a sequence, a series of these ridges often forms, called **scarp and vale topography**. The topography, or land surface, has scarps, or cuestas, divided by valleys or vales.

When the sequence dips more steeply than 10°, **ridges** of the harder rocks usually form, with steep slopes on either side (Figure 2.16).

Where large faults cut across the landscape, with different rocks on either side, then erosion tends to remove one type of rock at a faster rate than the other and a steep slope develops between the two rock types (Figure 2.17). This is called a **fault scarp** and, since such large faults are usually straight, fault scarps tend to cut straight across the country.

If the main rock underlying an area is granite, a tough erosion-resistant rock, it usually forms undulating upland areas with poor soils. Sometimes the granite is so resistant that it is exposed on the hilltops as rounded domes of jointed rock called **tors** (figure 2.18).

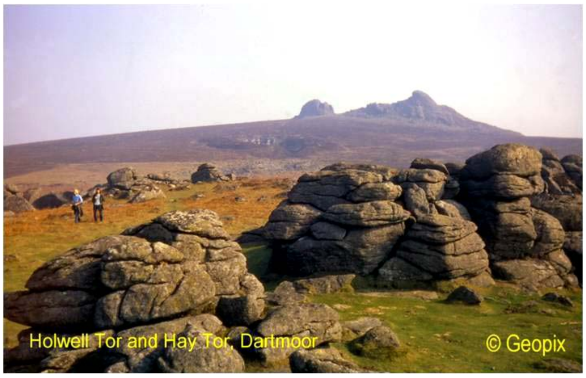
These features mean that you can stand on a hill top and look across at the shapes of the hills to see how the geology is lying. You can do the same in coastal areas, where the tough rocks form headlands and the weaker rocks form the bays between them (Figure 2.19). So a series of alternating tough and weaker rocks at the coast can form a series of headlands and bays. You can find out which of the rocks in your local area are likely to form hills and headlands, and which will form valleys and bays by doing the 'Rock, rattle and roll' test on the `http://www.earthlearningidea.com` website.

Try looking at the view from your window. Any hills or upland areas you can see are made of tougher rocks, while weaker rocks form any valleys or lowlands. Can you tell from the shapes of the hills what the underlying geology is like? You might be able to tell from the shape of any valleys you can see how they were formed as well.

Figure 2.15: A cuesta of gently dipping tough rocks with weaker rocks on either side. The rocks dip in the direction of the shallow slope

Figure 2.16: A ridge of steeply dipping rocks, with weaker rocks on either side.

Figure 2.17: A large fault has shattered and weakened the rock here, and it was later eroded into a valley by a glacier. A long narrow lake now fills the valley. The rocks on the right hand side of this view were tougher than those on the left, producing higher land and a steeper fault scarp slope.



Holwell Tor and Hay Tor, Dartmoor

© Geopix

Figure 2.18: An upland granite area with a jointed granite tor exposed on top of the hill.

Figure 2.19: This photo was taken from a headland of tough rocks, across a bay cut by erosion into weaker rocks, towards the tough rocks of another headland in the distance.

2.4 Modification of the landscape by human activity is often influenced by the underlying geology

Your view from a hill may have been changed by human activity, particularly if the underlying rocks are valuable or contain valuable minerals. You may be able to see active **quarrying** or **mining** activity in the distance (as in Figures 2.20, 2.21 and 2.22), or signs that quarrying or mining once took place there (Figure 2.23).

In the past, when the quarrying or mining activity stopped, the area was usually abandoned leaving tell-tale signs, like rock faces in unexpected places, hollows in the land surface or heaps of mining debris, abandoned buildings or other signs of activity. Things are very different today, since mining and quarrying companies have contracts that require them to leave the site in good condition when they leave (Figure 2.24). This may mean filling old quarries with waste material and planting vegetation to cover them, landscaping old tips of mining debris, removing old buildings and mining or quarrying gear, or allowing old pits to flood. These old mining areas are called ‘brownfield sites’ because of their industrial past, since if they are to be used for new buildings, remediation has to be carried out to remove any pollution and deal with dangers such as subsidence from old mine workings. ‘Brownfield sites’ contrast with ‘greenfield sites’ where no such remediation is necessary. Sometimes old mine or quarry workings are made into country parks, nature reserves or golf courses for people to enjoy. Some of the most visited areas near industrial cities are reclaimed mining and quarrying areas of the past.

Figure 2.20: A quarry in the distance.

Figure 2.21: A working quarry.

Figure 2.22: A working mine.

Figure 2.23: An abandoned mine.

Figure 2.24: A restored quarry. The old quarry has been filled, the surface landscaped and vegetation has been planted.

Figure 2.25: Dinosaur tracks conserved in an old quarry.

2.5 Important rock exposures should be conserved

Old quarries and mining areas can be excellent for wildlife, since they often have a wide range of environments, from rocky ledges where birds can nest, to marshy areas for wetland creatures. However, some are worth preserving because of their geological interest. For example, it is important to preserve dinosaur tracks (Figure 2.25) and trails or fossil forests, but it may be equally important to preserve small fossil sites, or areas where rock-forming environments can be seen particularly easily. In the UK, sites of particular scientific interest, that can be both biological or geological, are identified as '**Sites of Special Scientific Interest**'. SSSIs cannot be used for development unless special permission is granted. Other sites that don't have national importance, but are still valuable for scientific or educational purposes are designated in the UK as '**Regionally Important Geological and Geomorphological Sites**' (RIGS). Really large and important areas can be designated as World Heritage Sites, such as the 'Jurassic Coast' along the coastline of Southern England, whilst many regions across the world are being given

Figure 2.26: A castle on a volcanic plug in the Bohemian Paradise Geopark.

Figure 2.27: Hazardous material in an old metal-mining area

Geopark status by UNESCO (the United National Educational, Scientific and Cultural Organisation) because of their geological importance and interest; Figure 2.26 shows an example.

Old mining and quarrying areas that have been conserved have been risk-assessed for health and safety and, providing visitors are sensible, the risks are small. However, the same cannot be said for other abandoned and working sites, which can be very dangerous areas (Figure 2.27). Working sites usually have good fencing with warning signs, but abandoned sites may have no warnings. There are particular dangers from unstable rock faces, old mine shafts or entrances that may not have been capped properly, old dams full of mud from mine workings, and quarries flooded with water that is often very deep and cold.

The Geological Fieldwork Code, published by the Geologists' Association, provides the following guidance for people visiting field sites in the UK, whether they are natural exposures or rock faces in old mining or quarrying areas. Similar guidance should be followed when visiting any geological sites across the world.

GEOLOGICAL FIELDWORK CODE

- Obey the Country Code and observe local bye-laws. Remember to shut gates and leave no litter.
- Always seek permission before entering onto private land.
- Don't interfere with machinery.
- Don't litter fields or roads with rock fragments that could cause injury to livestock or be a hazard to vehicles or pedestrians.
- Avoid undue disturbance to wildlife. Plants and animals may inadvertently be displaced or destroyed by careless actions.

- On coastal sections, whenever possible consult the coastguard service about tides or local hazards such as unstable cliffs.

- When working in mountains or remote areas, follow the advice given in the booklet “Safety on Mountains” issued by the British Mountaineering Council, and in particular inform someone of your intended route.

- When exploring underground, be sure you have the proper equipment and the necessary experience. Never go alone. Report to someone your departure, location, estimated time below ground and then your actual return.

- Don’t take risks on insecure cliffs or rock faces. Take care not to dislodge rock: others may be below.

- Be considerate. Don’t leave an exposure unsightly or dangerous for those who come after you.

Chapter 3

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

3.1 The rock cycle (Hutton, 18th Century)

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.

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.’

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';

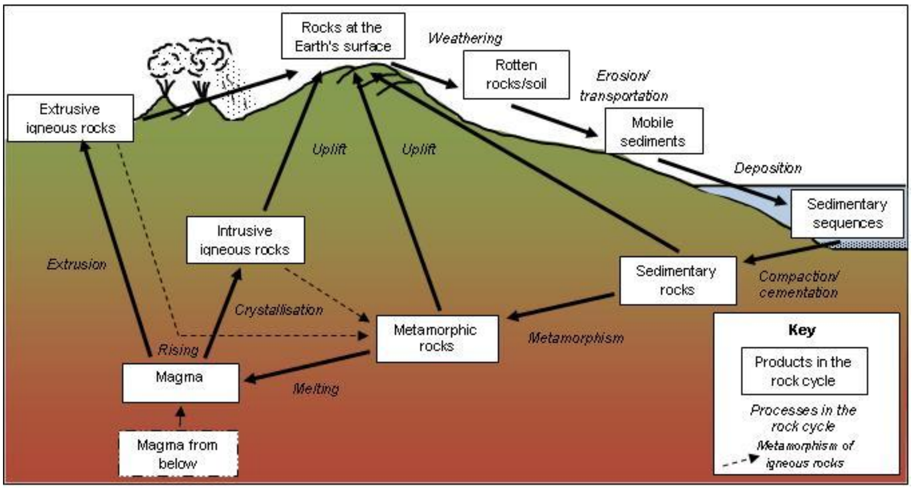


Figure 3.2: The rock cycle, as we know it today.

- 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.

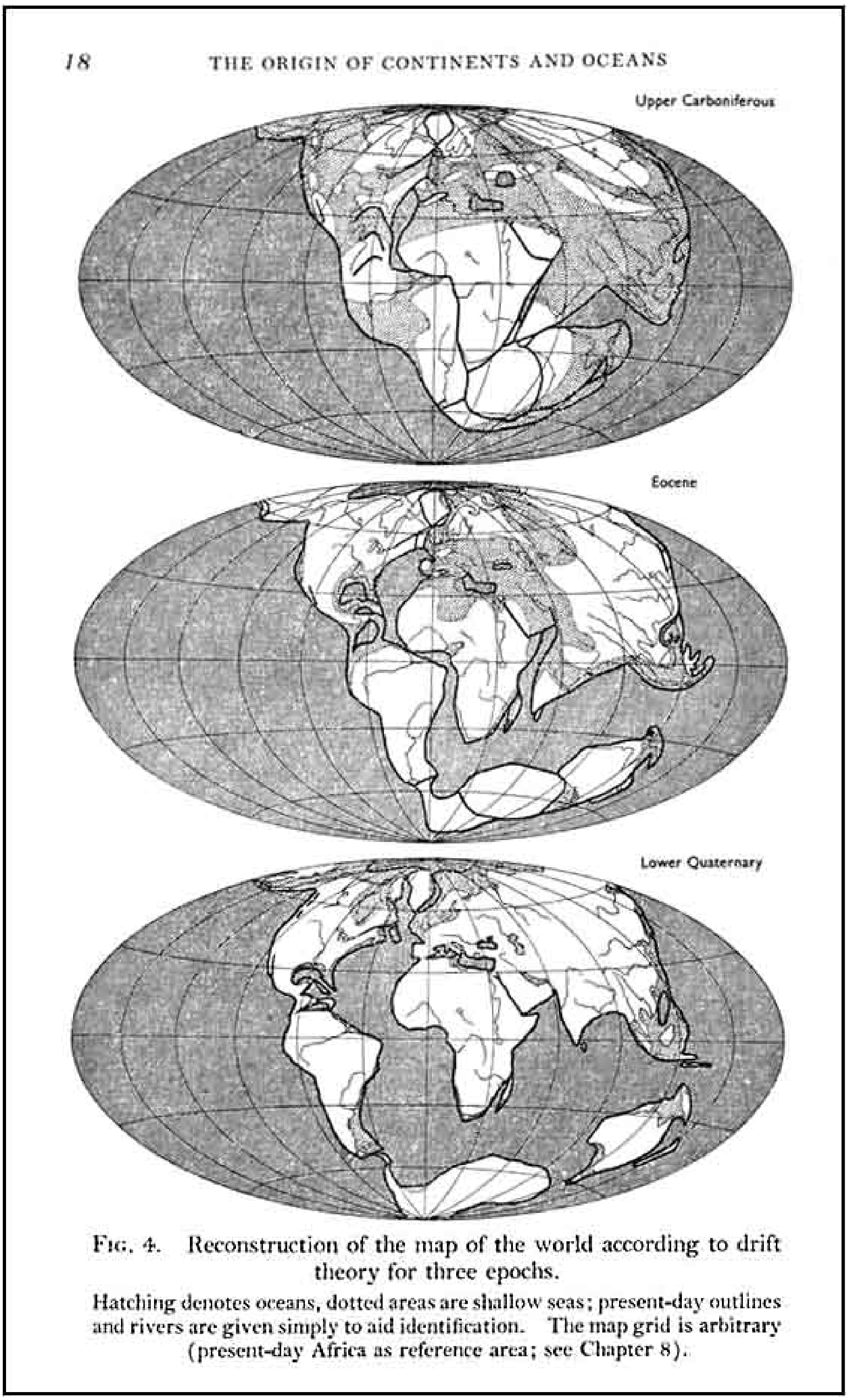
3.2 Plate tectonics (20th Century)

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;



18 THE ORIGIN OF CONTINENTS AND OCEANS

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.

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

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.

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

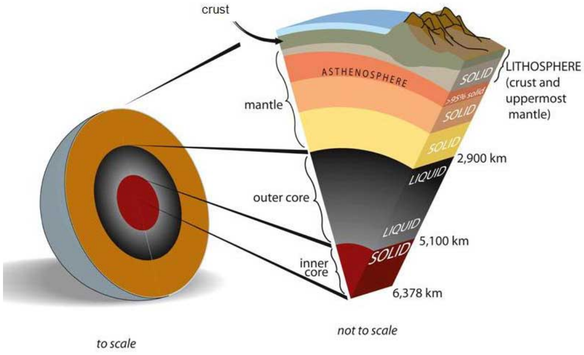


Figure 3.7: The structure of the Earth, showing the lithosphere and asthenosphere (not to scale).

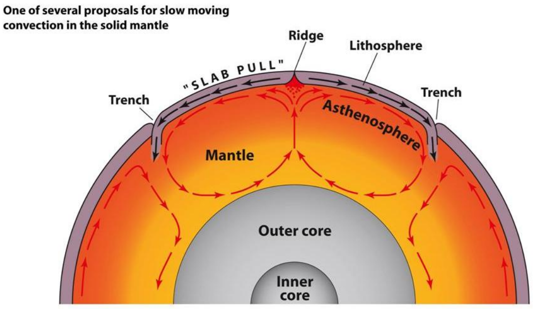


Figure 3.8: Convection currents in the mantle.

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

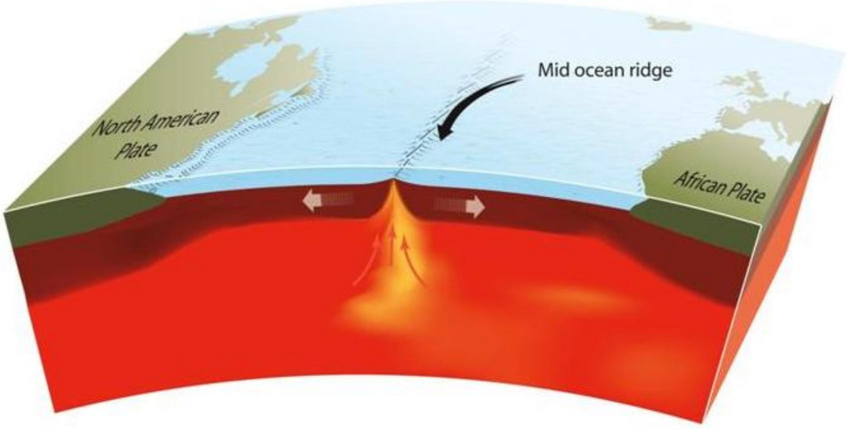


Figure 3.9: The Mid-Atlantic Ridge.

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

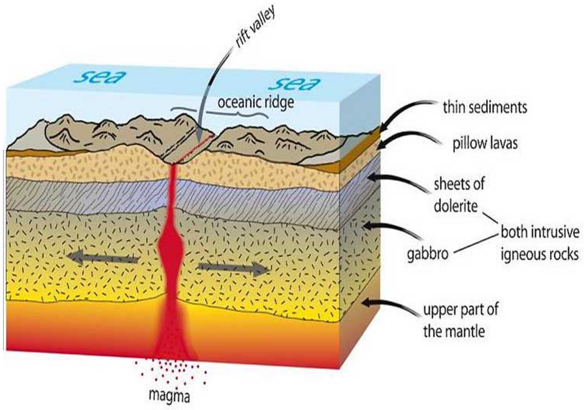


Figure 3.11: A constructive boundary, where new oceanic plate is being formed.

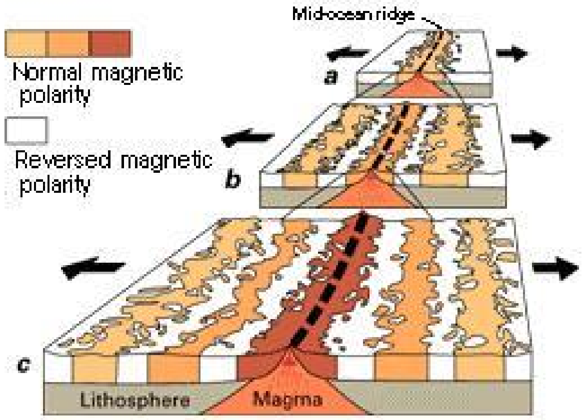


Figure 3.12: The formation of magnetic stripes at a constructive plate margin.

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

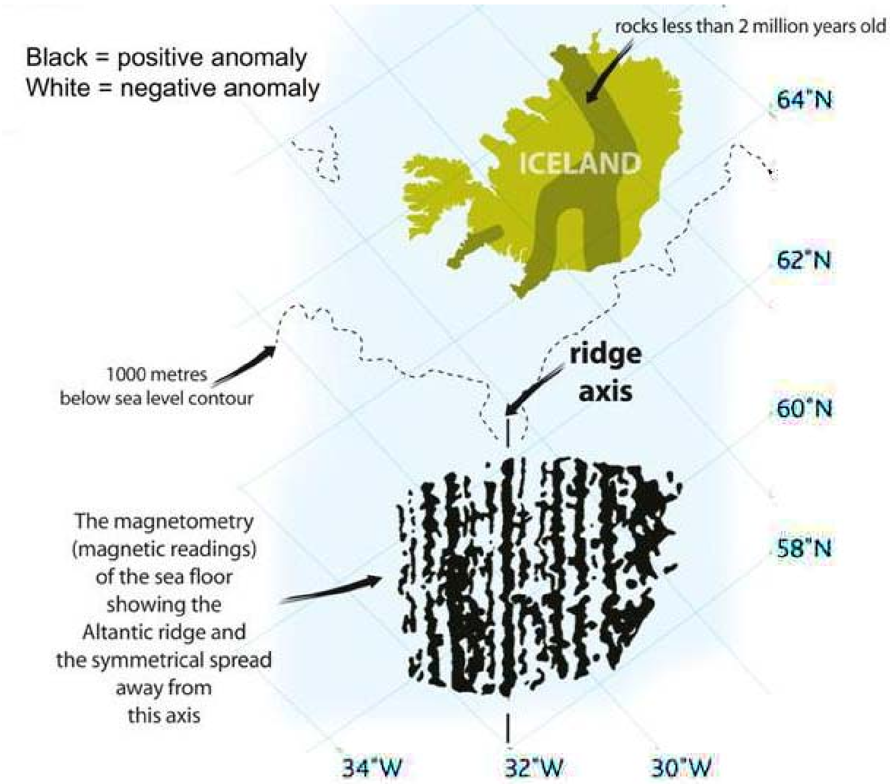


Figure 3.13: The magnetic stripes south of Iceland.

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

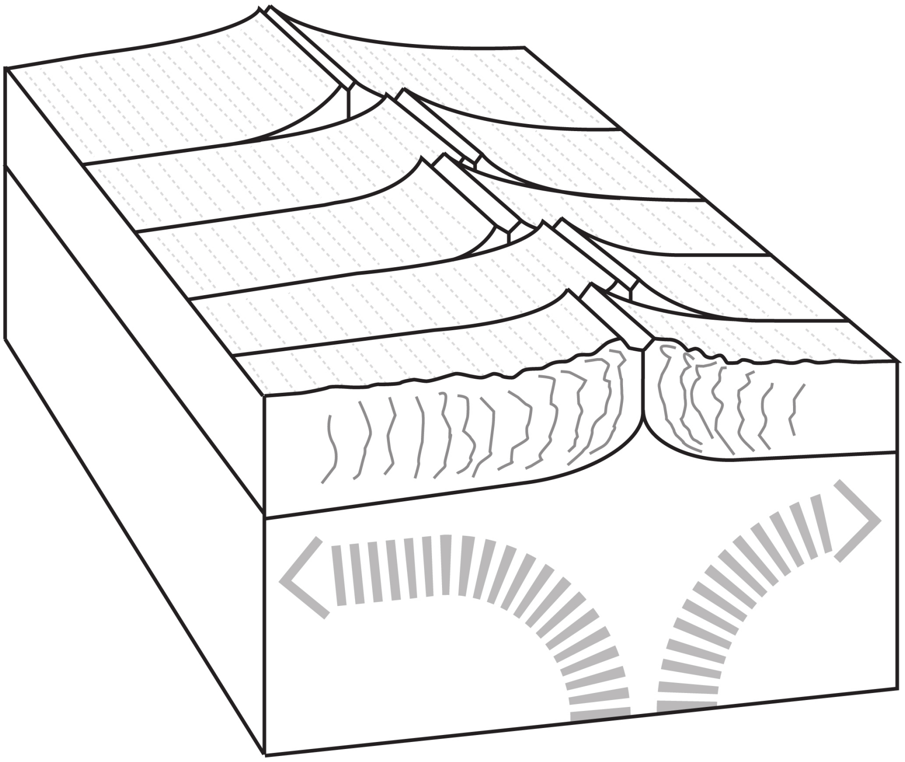


Figure 3.14: Oceanic ridges are offset by transform faults.

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’. 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.

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.

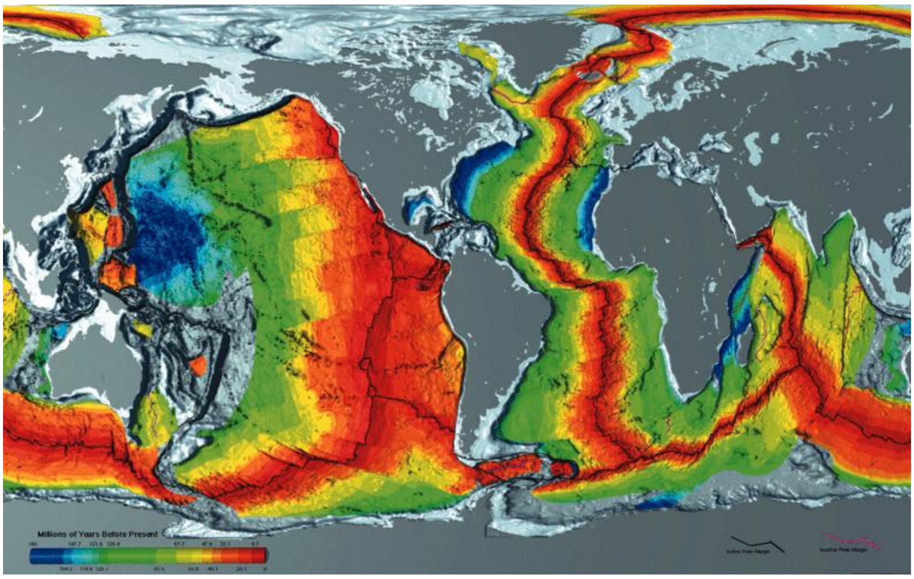


Figure 3.16: The age of the ocean floor, from the youngest in red to the oldest in blue.

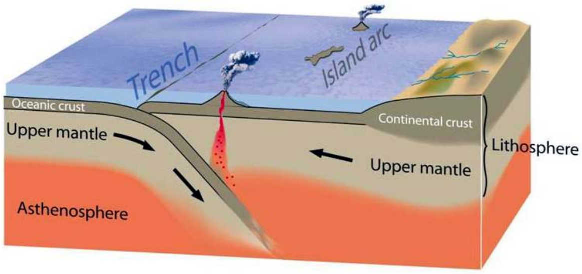


Figure 3.17: An ocean versus ocean destructive margin, with an oceanic trench and an arc of destructive andesitic volcanoes.

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

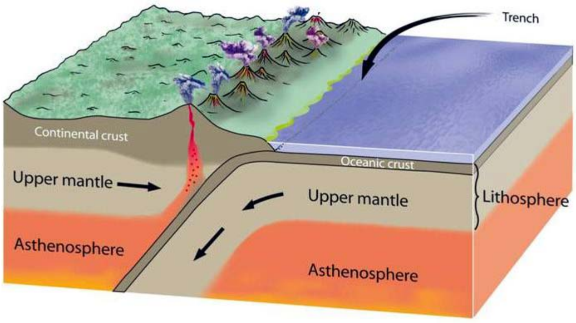


Figure 3.19: An ocean versus continent destructive margin, with an oceanic trench and a mountain range with volcanoes.

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

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 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.

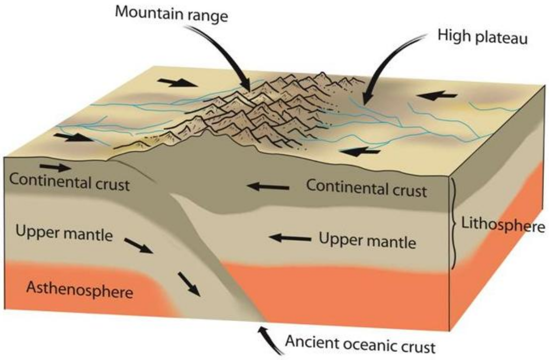


Figure 3.21: A continent versus continent destructive margin.

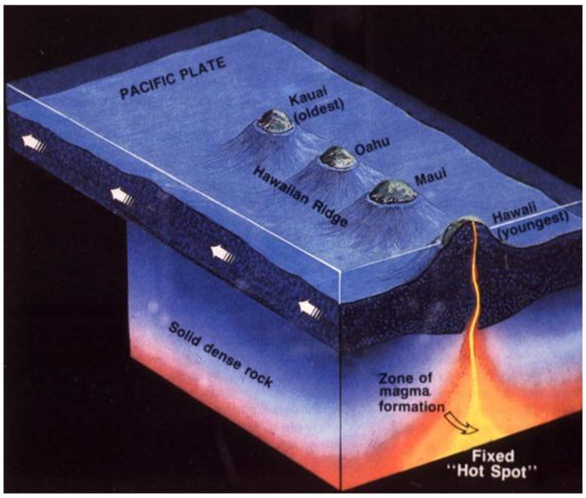


Figure 3.22: The Hawaiian island chain, formed as the Pacific plate was moved across a hot spot in the mantle.

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 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.

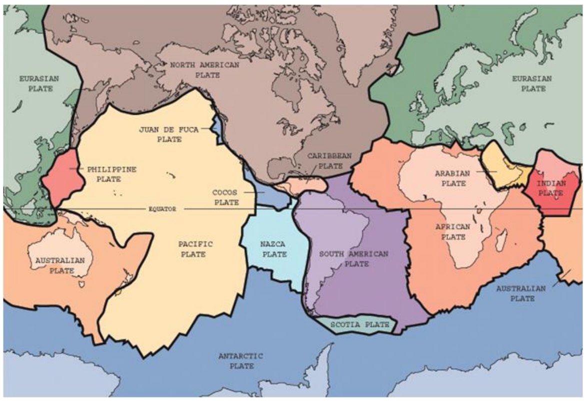


Figure 3.23: Map of the major tectonic plates on Earth.

Figure 3.24: Stromatolite fossils in ancient rocks.

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**

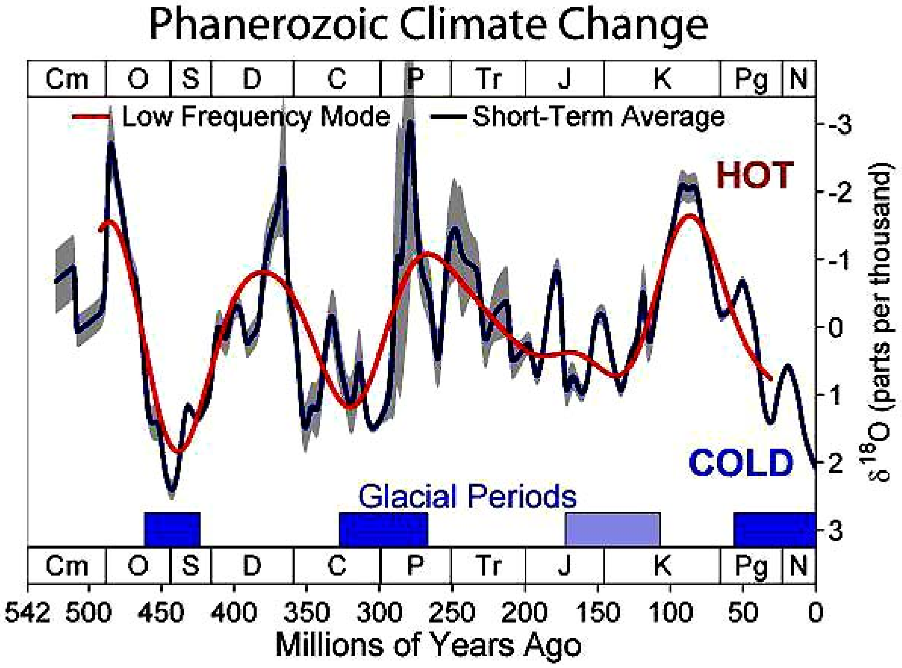


Figure 3.25: Global temperature change over the last 500 million years (the Phanerozioc time period), obtained by measuring change in the oxygen isotope compositions of fossils.

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 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

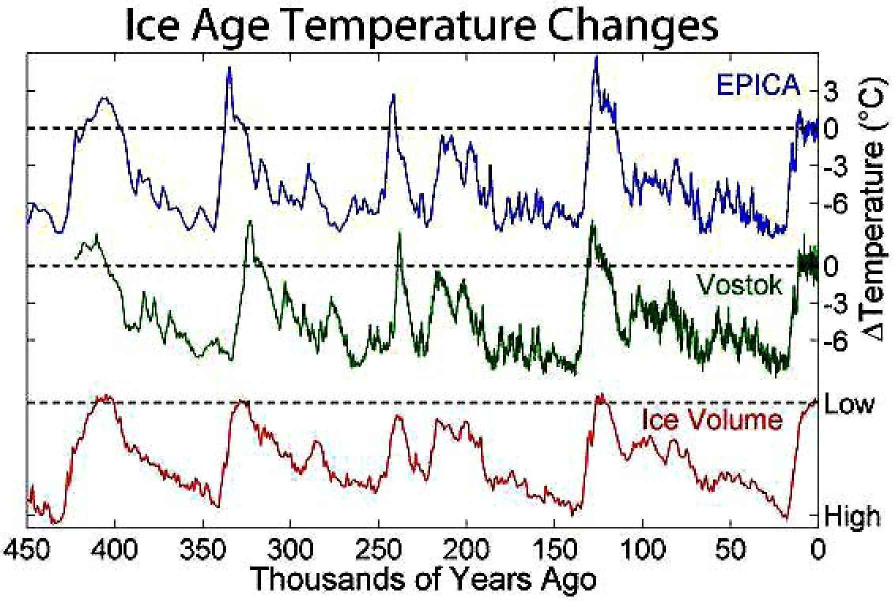


Figure 3.26: Global temperature change over the last 450 thousand years, obtained from duterium isotope measurements. The ratios were measured in the EPICA and Vostock ice cores and have been converted to ice volume estimations in the lower graph.

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 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

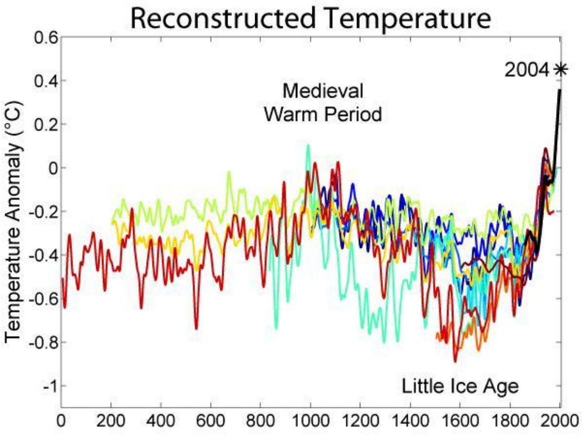


Figure 3.27: Global temperature change over the last 2000 years, compiled from 10 different sources (shown in different colours), including tree ring and glacial data.

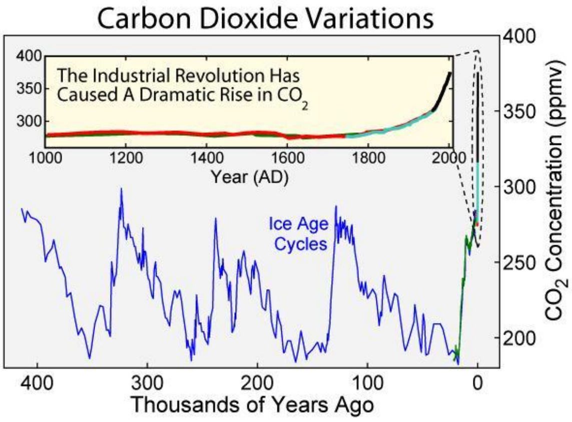


Figure 3.28: The amount of carbon dioxide in the Earth's atmosphere over the past 40,000 years and (inset) the last 1000 years, measured from the bubbles of air trapped in ice cores.

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 remained 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.

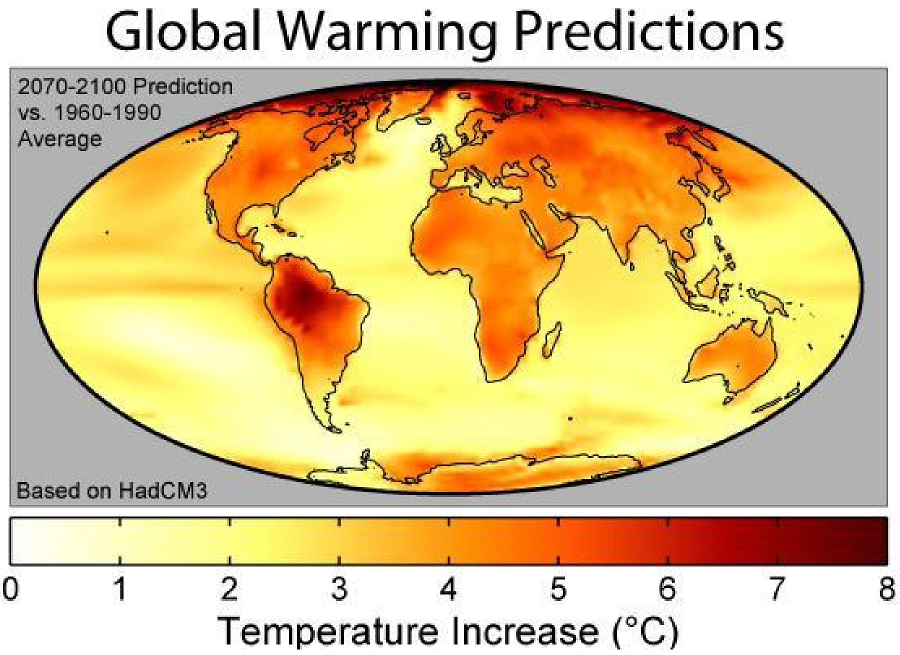


Figure 3.29: A computer generated prediction for the global effects of a 3°C increase in global temperature.

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 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.

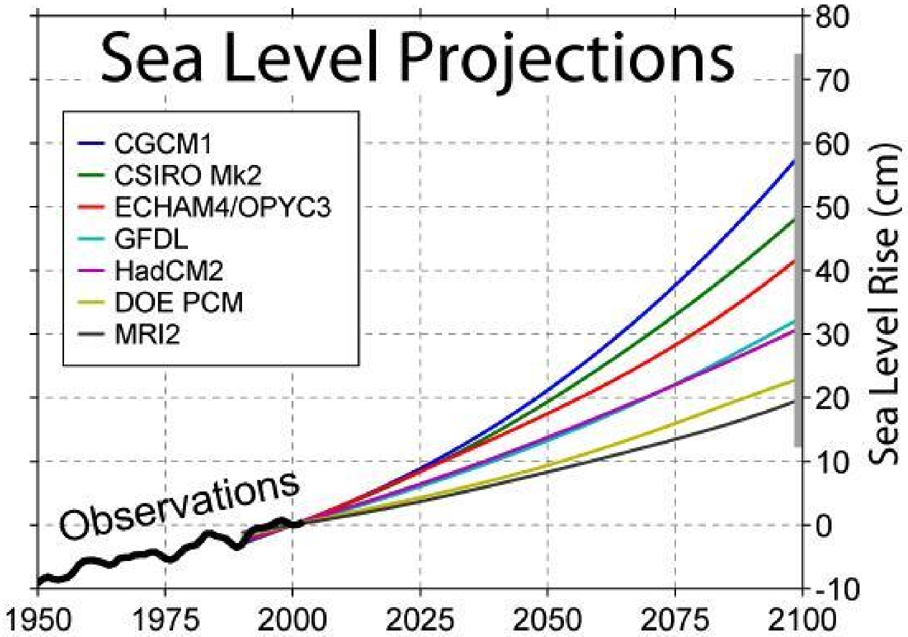


Figure 3.30: A graph of observed increases in seal level over the past 50 years with projections of the effects of the melting of continental ice sheets in the next 100 years.

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 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

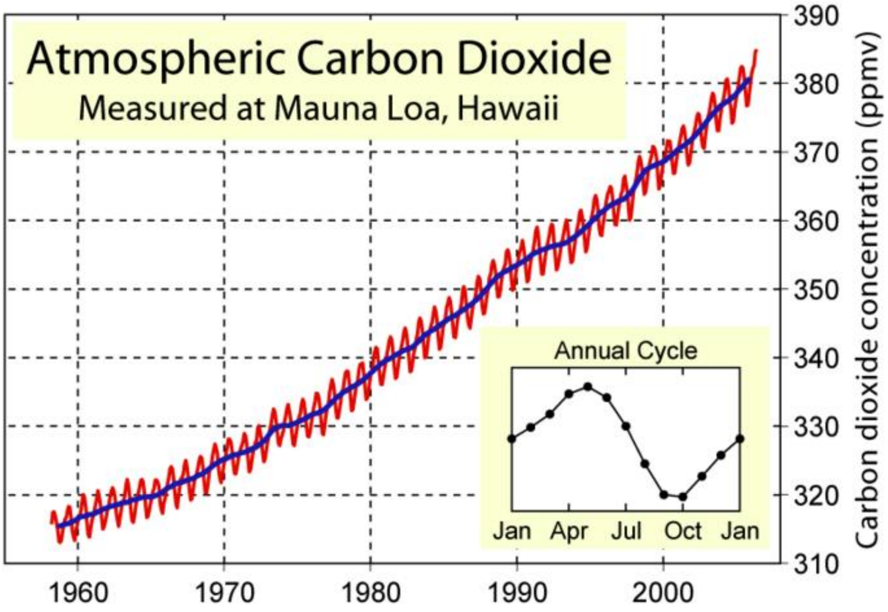


Figure 3.31: The 'Keeling Curve' of atmospheric carbon dioxide measurements, showing annual cycles and a steady increase.

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. 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.

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

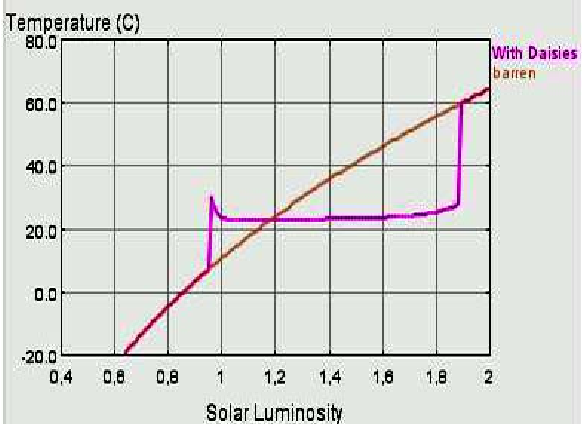


Figure 3.33: One of James Lovelock's 'Daisyworld' simulations, showing that life could maintain a steady temperature on a planet, as solar radiation increases.

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 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.

Chapter 4

Major geological events fit into a timeline, beginning with the formation of the Earth

4.1 The origin and development of life

William Smith was a canal engineer who supervised the excavation of boat canals across England in the late 1700s and early 1800s. When cuttings for the canals had to be made through hilly areas, he noticed that the layers of sedimentary rock always formed the same sequence. He also noted that the same layers always contained the same fossils and that the sequence of fossils was always the same. He called this his 'Law of Faunal Succession' and this helped him to link together rocks from different parts of the country because they contained the same fossils. This is a method we now call correlation. By correlating rock sequences across the country, Smith was able to produce a geological map of England and Wales (shown in Figure 4.1), the first geological map of a country ever produced (although geological maps of smaller areas had previously been made in Europe).

Smith knew that fossils occurred in a certain sequence in rocks - but he didn't know why. In fact most people at that time (with the exception of a few scientists) didn't even question the meaning of the fossils in rocks, believing that all rocks had been formed, with fossils inside some of them, during creation a few thousand years before. It wasn't until Charles Darwin proposed his theory of evolution by natural selection that a reason for the sequence of fossils in the rock was provided. Darwin published his book, 'On the origin of species by natural selection' in 1859, basing it on his reading of other scientific publications and a mass of geological and biological evidence he had collected himself. He realised that when plants and animals reproduce, they produce new young organisms, some of which are better adapted to the environment than others. Through '**natural selection**' the best adapted ones survive and the less well adapted ones die. This means that slightly different, better-adapted organisms develop and, if this continues, whole new types of organisms can form as one species develops into another through evolution. This explains why different rocks contained the different fossils that William Smith had

Figure 4.1: William Smith's geological map of England and Wales, published in 1815, made using his 'Law of Faunal Succession'.

Millions of years ago (Ma)	Some Major Life Events
2	First humans (genus Homo)
65	Major extinction of life on Earth, including dinosaurs
130	First flowering plants
150	First birds
190	First mammals
200	Major extinction of life on Earth
225	First dinosaurs
250	Major extinction of life on Earth, including most marine organisms
315	First reptiles
365	Major extinction of life on Earth
370	First amphibians
420	First plants and animals on land
450	Major extinction of life on Earth
510	First fish
545	First animals with hard parts
1200	First multicellular organisms
2000	First eukaryotes (cells with a nucleus)
3500	First bacteria and archaea (cells with no nucleus)
3800	Earliest life
4600	Origin of the Earth

Figure 4.2: Key events in the evolution of life. In this table Ma means "Millions of years ago".

observed and why the sequence is always the same, because this sequence of evolution has only happened once.

Since Darwin's time we have discovered more about the mechanisms of evolution, how parents pass their characteristics onto their offspring through their DNA and how different adaptations can develop, but the principle that Darwin discovered remains the basis of our understanding of life on Earth. The evidence from the rocks shows us the sequence of life on Earth, and the evidence from the DNA of modern organisms (DNA is deoxyribonucleic acid which holds the genetic information of all organisms) shows how this sequence developed.

Some of the key events in the evolution of life are shown in a table in Figure 4.2, but a table like this does not show how these events are spaced out over geological time. The time line in Figure 4.3 attempts to show some of the key life events in this way.

Although we know that the age of the Earth is about 4,560 million years, from radiometric dating, we don't know exactly when or how life on Earth began. Probable fossils of mats

Millions of years ago (Ma)	**Some Major Life Events**	
0 1000	First humans (genus *Homo*) (2) First flowering plants (130) First mammals (190) First reptiles (315) First animals with hard parts (545)	Major extinction (65) First birds (150) Major extinction (250) Major extinction (450)
2000	First multicellular organisms First eukaryotes (cells with a nucleus)	
3000		
4000	First bacteria and archaea (cells with no nucleus) Earliest life	
	Origin of the Earth	

Figure 4.3: Key events of life shown on a geological time line.

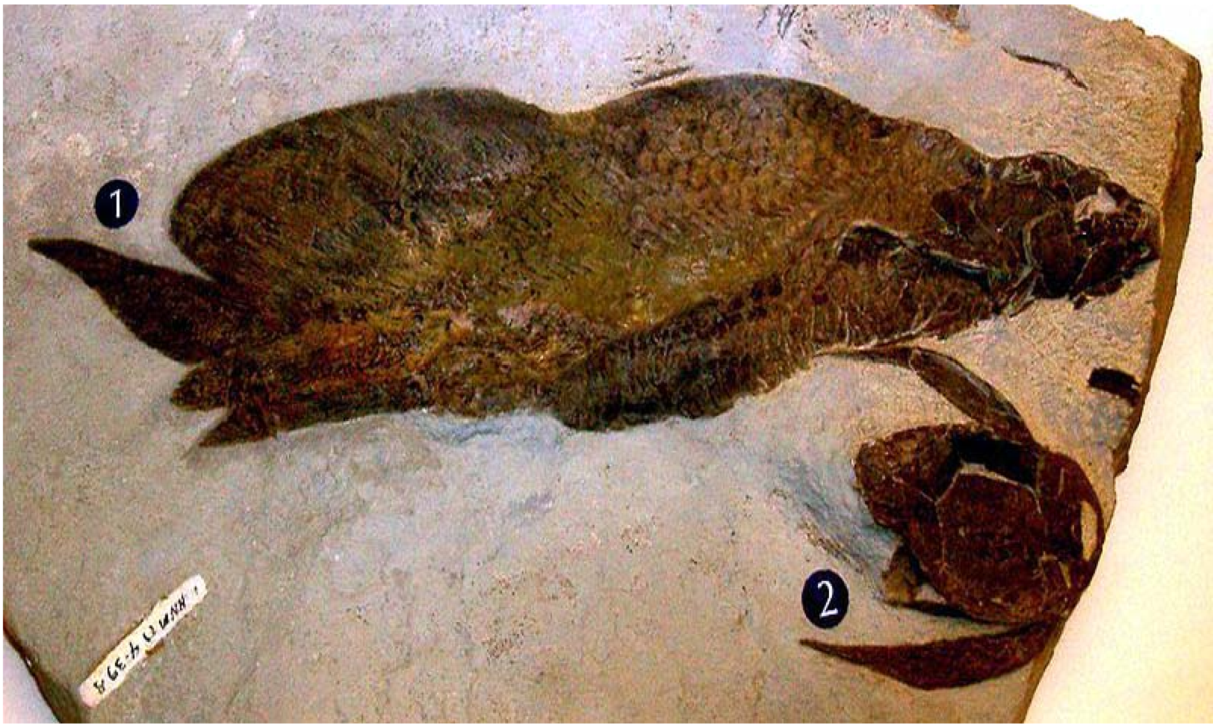


Figure 4.4: Two early fossil fish

of simple organisms, forming layers over the sediment surface, have been found in 3,500 million year old rocks - indicating that life on Earth must have begun even earlier. A range of different ideas about how early life might have formed has been suggested. These include, among others, that early life formed in the oceans from the effects of ultra-violet light or lightning on simple organic molecules, and that life formed first in hydrothermal vents on the deep ocean floor through the reactions of iron and sulfur compounds at temperatures over 100 °C.

A key characteristic of life is the ability to evolve. Simple cells with no nucleus (bacteria and archaea) were the first life forms to evolve, producing mats of organisms in rocks 3500 million years old; some of these later formed short pillars of mats called **stromatolites**. These simple organisms with no nucleus, went on to dominate the Earth in terms of numbers. Today they form more than 99% of life and have sometimes adapted to live in extreme conditions, such as with no light, or oxygen or at high temperatures. They live in all environments known on Earth and are particularly important to the weathering that forms soils.

A key evolutionary event was when two simple-celled organisms evolved to work together in a relationship that benefited them both. They became **eukaryotes**, cells with nuclei. Fossils of these have been found in rocks 1600 million years old and possibly of 2000 million years old. One of the first multi-celled organisms to evolve were red algae, which are preserved in 1200 million year-old Canadian rocks. The first organisms that were probably animals were similar to corals and are found as fossils in 580 million year old rocks whilst the first definite plants were not fossilised until a little later in geological time.

Before 542 million years ago, all organisms had **soft bodies** and so were rarely fossilised and are very uncommon. However, after 542 million years, many groups had evolved **hard parts**, usually to protect them from the environment and predatory animals around them, so we suddenly find fossil life much more common in the rocks. Fossils of the first fish are found in 510 million year old marine rocks (Figure 4.4). Some of these later developed limbs that they could use to drag themselves onto the land and evolved into amphibians, the first fossils of these being found in rocks around 370 million years old (Figure 4.5). A wide variety of amphibians developed, large and small; frogs and newts are common amphibians alive today and like their ancestors, have to return to water to reproduce and lay their eggs.

Around 315 million years ago, the earliest reptiles evolved, with the ability to lay eggs on land and to walk more efficiently (Figure 4.6). Reptiles went on to 'rule the world' and evolve into **dinosaurs** before the dinosaurs became extinct 65 million years ago, leaving modern reptiles like crocodiles and lizards.

It took several millions of years for mammals to evolve from reptiles, and the first true mammal fossils are around 190 million years old (Figure 4.7). Soon afterwards, birds also evolved from reptiles and the first bird fossils are found in 150 million year old rocks (Figure 4.8). Meanwhile, flowering plants evolved from non-flowering plants and the first flowers were seen on Earth about 125 million years ago. One of the latest groups to form developed into humans, with the first fossils of the genus *Homo* being found in rocks just 2 million years old. You can illustrate the evolution of life on Earth using the 'Timeline in your own backyard' activity from `http://www.earthlearningidea.com`.

This may read as though life showed a steady evolution over time, but this is far from true. There have been at least five major periods of **mass extinction** recorded in the fossil record (Figure 4.2), and probably more before that, when the fossil record was poorer. This is in addition to the many minor episodes of **extinction** that have also taken place shown on the graph in Figure 4.9. In the mass extinction of 250 million years ago 'nearly all life died' as indicated by the title of a popular book describing this major catastrophe for the Earth. Mass extinctions are important because, when whole groups or organisms have become extinct, other groups of organisms have the chance to take over the environment in which they lived (their **ecological niche**) afterwards. Thus the extinction of the dinosaurs allowed the mammals to become much more successful and take over many of the ecological niches in which the dinosaurs used to live.

Many theories have been put forward over the years that might account for extinctions, both major and minor. These have included climate change, possibly triggered by widespread volcanic eruptions, and the impact of **asteroids** having dramatic effects across the Earth.

As Darwin suspected, one of the driving forces of evolution has been separation. When groups of animals became separated, as for example, on an island or in a large lake, they evolved without any outside influences and new species developed. When these new species later rejoined the other groups, some were successful and joined or overtook

Figure 4.5: A fossil amphibian.

Figure 4.6: A fossil reptile.

Figure 4.7: A fossil mammal

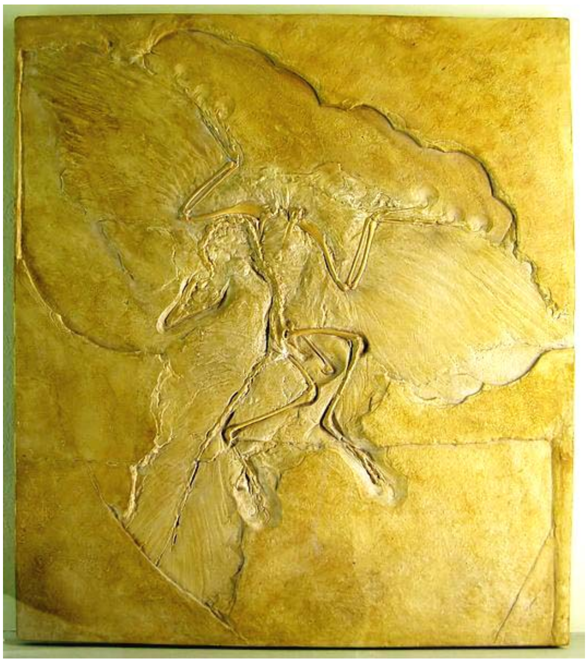


Figure 4.8: The earliest fossil bird that has been found - *Archaeopterix*.

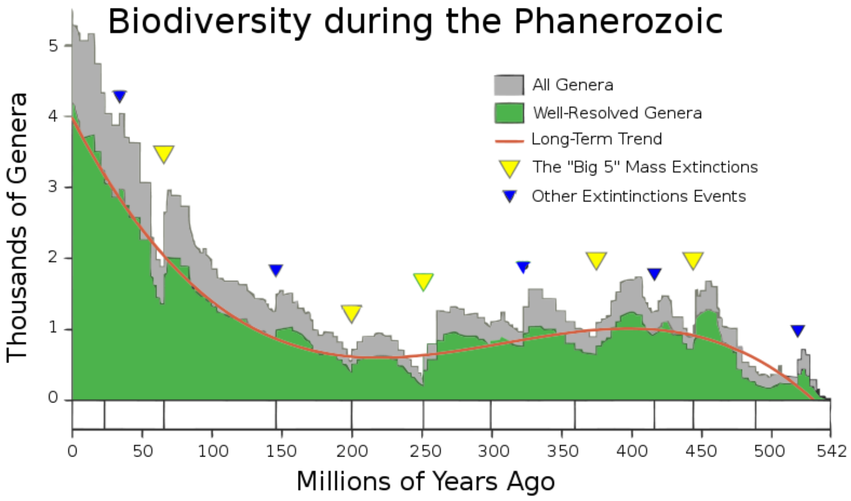


Figure 4.9: The change of biodiversity over time - showing major extinction events.

the other groups, whilst others died out. In the geological past, separation and joining have been caused by the movement of plates, thus plate tectonic movement has been an important component of evolution on Earth. One of the human influences on Earth has been to move organisms around the planet resulting in a ‘joining’ of groups. This, together with the major human impacts on a wide range of environments across the Earth, has caused the extinction of many organisms in recent times. Some scientists argue that this could result in a mass extinction on the scale of some of the previous mass extinctions on Earth.

Although one way of working out relationships between groups of organisms is to try to find out their evolutionary sequence from the fossil record, a second method compares the features of different groups of organisms to work out the relationships between them. Similar organisms are allocated to a group, called a clade, and the relationships of clades to one another is shown in a cladogram. The cladograms in Figures 4.10 and 4.11 show how early organisms were related and how vertebrate animal groups are linked to one another.

4.2 The development of Earth’s continental jigsaw

The first continents were formed around 4000 million years ago by processes similar to the plate tectonic processes we see today, and there is evidence that the early igneous rocks that formed the continents were metamorphosed and subject to sedimentary processes just like continental rocks today. Since these small early continents were made of low density silica-rich rocks, they were too light to be carried back into the Earth by subduction and so remained on the surface to be carried around by early tectonic plates. As they were moved around, they sometimes collided and the new rocks formed in the collision zones ‘stuck’ the continents together to form larger continents.

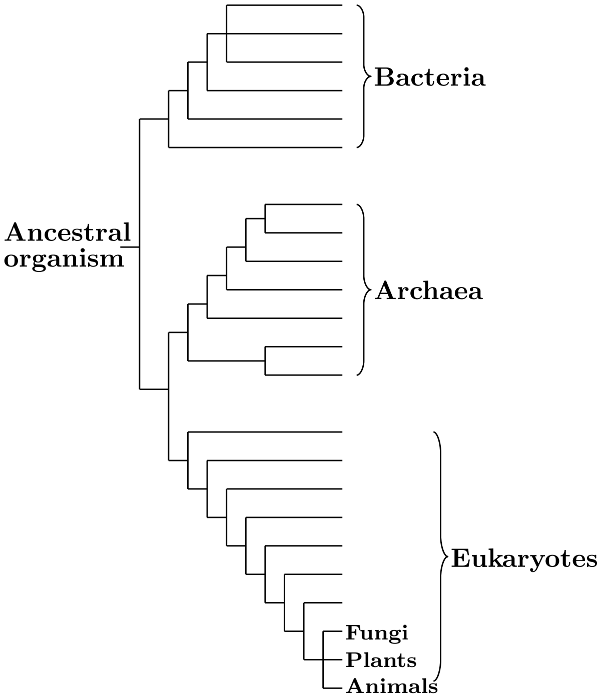


Figure 4.10: A cladogram showing the relationships of the major groups of life on Earth.

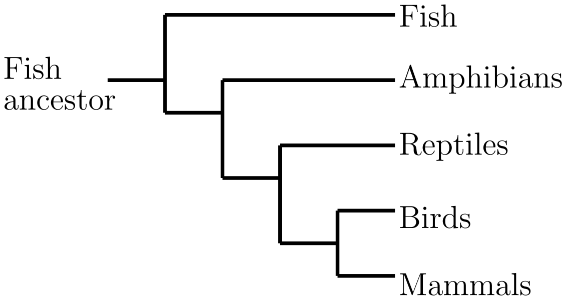


Figure 4.11: The relationships of major animal groups, shown by a cladogram.

Around 1000 million years ago, all the continents had combined together into one huge landmass in the southern hemisphere that we call **Rodinia**. This **supercontinent** began to break up around 750 million years ago and the different continents were shuffled around, but by about 550 million years ago all the major continents that now form the southern hemisphere continents (today's South America, Africa, Australia and Antarctica - with India as well) had recombined into another supercontinent that we call **Gondwana**, whilst the continents that we now identify as North America, Europe and Siberia were all separate (Figure 4.12). As time moved on, 'North America' collided with 'Europe' as the Gondwana continent moved northwards towards them (Figure 4.13)

Between 300 and 250 million years ago all the major continents on Earth had been joined together again to form the largest supercontinent ever seen on Earth (Figure 4.14), that we call **Pangaea**. Then Pangaea began to split apart, forming first the North Atlantic Ocean and later the South Atlantic Ocean, as Antarctica, Australia and India separated from Africa. By around 100 million years ago, all the major continents we recognise today had separated from one another (Figure 4.15).

The continents continued to move, India collided with Asia forming the Himalayan mountain range, and Africa impacted on Europe forming the Alps. All the continents moved

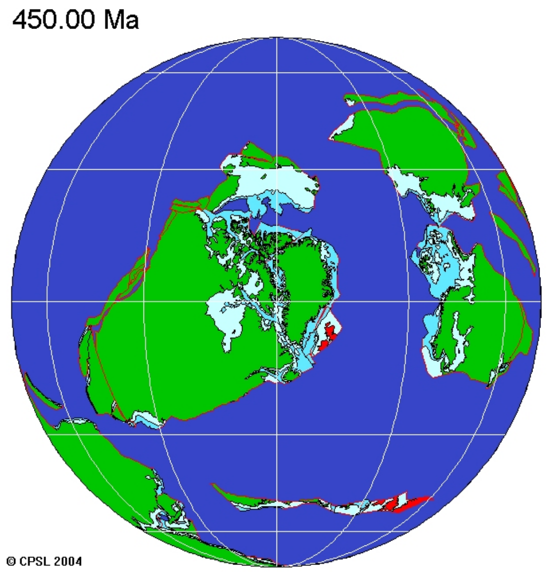


Figure 4.12: The 450 million year old Earth. Separate ‘North America’, ‘Europe’ and ‘Siberia’ with Gondwana formed of all today’s southern hemisphere continents on the other side of the globe.

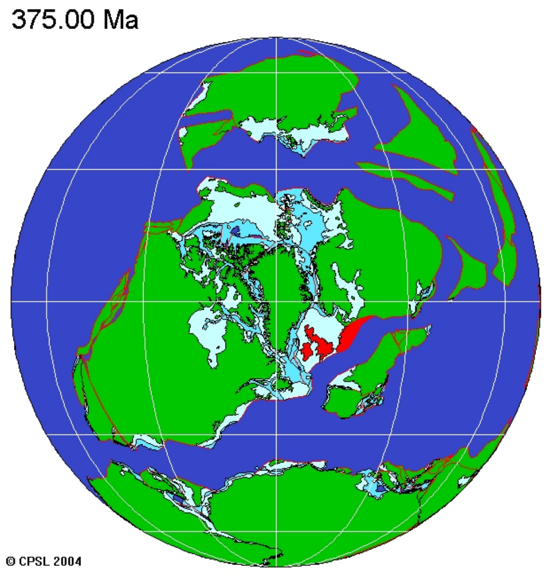


Figure 4.13: The 375 million year old Earth, after the collision of ‘North America’ with ‘Europe’.

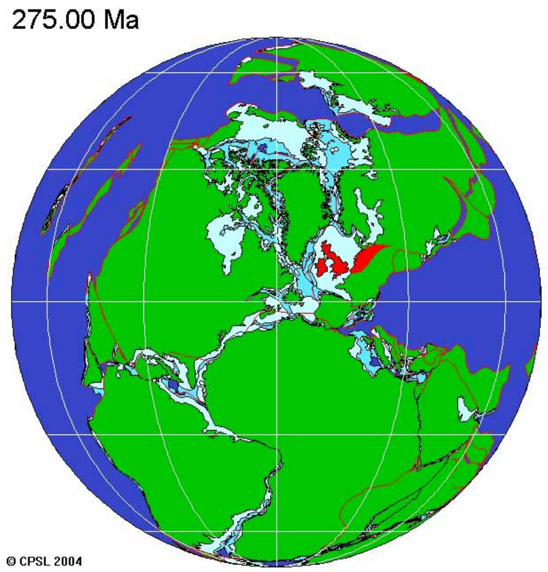


Figure 4.14: Supercontinent Pangaea, 275 million years ago.

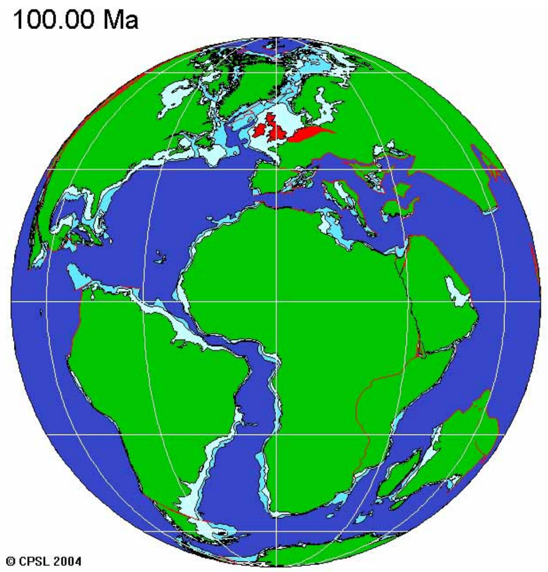


Figure 4.15: Continents on the 100 million year old Earth.

into the positions they have today - but they continue moving, at centimetres per year, so the distribution of continents on Earth will continue to change into the future.

This movement of plates and continents over geological time has had profound effects; oceans have formed and closed, continents have grown and split, and plate movements have produced mountain ranges which were later eroded.

As the plates and continents were moved across the Earth, they encountered different climates in different parts of the globe. So a continent like India, that at one time was near the south pole experiencing polar conditions, was moved north, through temperate and tropical zones and across the equator, to its present position. The sedimentary rocks laid down when it was in each climate zone record the story of this movement over the surface of the Earth. The rock sequence also records evidence of tension, as plates moved apart, and compression, as plates collided, during its long geological history.

As well as all these changes, that are clearly linked to plate movement, there were global changes as well. At times, global sea levels have been much higher than today. These high sea levels seem to be linked to times when new oceans were forming, with active constructive plate margins swelling up and displacing much of the ocean water on to the land.

Great variations in global climate may also be linked to plate activity so, for example, the intense ice ages that affected Earth between 900 and 600 million years ago, may be related to quieter times in plate movement when reduced volcanic activity at plate margins produced less carbon dioxide and the globe cooled. At times during these global cooling events 600 - 900 million years ago, the Earth may have been completely covered by ice - a ‘**Snowball Earth**’ or nearly covered by ice - a ‘**Slushball Earth**’. Ice ages which did not affect the whole globe, but which nevertheless had important effects near the poles also occurred around 460 and 300 million years ago and Earth today is still experiencing an ice age that began 2 million years ago. These are called ‘**ice house conditions**’, contrasting with the ‘**greenhouse conditions**’ when the Earth was completely ice-free at the poles. One period of ‘greenhouse conditions’ occurred when Earth experienced extreme global warming 55 million years ago.

All these events build into a picture of the complex evolution of our planet with a number of major ‘milestones’ along the way (shown in Figure 4.16).

Earth is clearly a very dynamic planet, with the continents experiencing great changes of latitude and altitude whilst also being affected by global sea level and temperature changes. These changes have affected life on Earth by separating and joining populations of organisms whilst creating and destroying environmental niches. Now humans are having an additional impact of global importance that can only have more effects on the Earth in the future.

Millions of years ago (Ma)	**Some Major Earth Events**
2	Ice age
55	Extreme global warming
65	Major extinction of life on Earth, including dinosaurs
130	First flowering plants
150	First birds
190	First mammals
200	Major extinction of life on Earth
225	First dinosaurs
250	Major extinction of life on Earth, including most marine organisms
300+	Ice ages
315	First reptiles
325+	Supercontinent Pangaea existed
365	Major extinction of life on Earth
370	First amphibians
420	First plants and animals on land
450	Major extinction of life on Earth
460	Ice age
510	First fish
545	First animals with hard parts
600 - 900	Ice ages
1000+	Supercontinent Rodina existed
1200	First multicellular organisms
2000	First eukaryotes (cells with a nucleus)
3500	First bacteria and archaea (cells with no nucleus)
3800	Earliest life
4000+	Earliest continents formed
4600	Origin of the Earth

Figure 4.16: ‘Milestones’ in the evolution of planet Earth

Chapter 5

Current geological events commonly reported in the media

5.1 Earth hazards

Geological events and activities are frequently reported in newspapers, on the radio and TV, and on the internet, but quite often it is clear that the reporter didn't have a good understanding of the geoscience being reported. The most common reports refer to geological hazards, climate change, fossil finds and local issues such as quarrying and landfill and the background to all these aspects is given below.

Earth processes can destroy single buildings and whole regions and it is the fast-acting large-scale processes that are most destructive. Earthquakes themselves can be highly dangerous and even more so when they trigger landslides or tsunamis. Small, 'safe' earthquakes occur in most parts of the world most of the time, caused by flexing of the moving plates, but large earthquakes are most common at the active margins of plate boundaries.

Figure 5.1: A school in San Salvador destroyed by an earthquake.

Most earthquakes occur when plate movement causes pressures to build up in the crust. When the pressures become too high, the rocks fracture along a fault, rather like the way a piece of wood snaps when you bend it too much. The

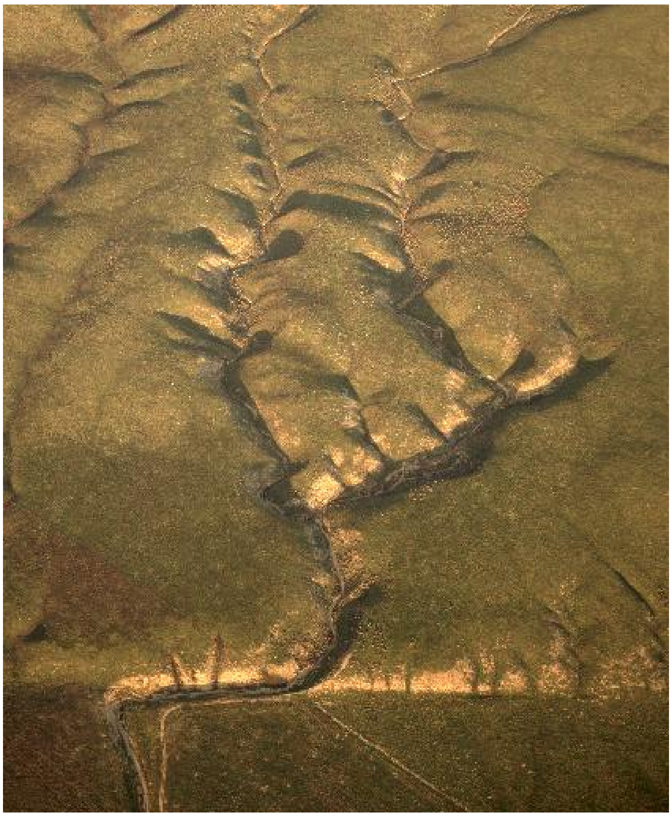


Figure 5.2: Strike-slip movement (rocks in the lower part of the photo to the left) along the San Andreas transform fault in California, USA.

two sides spring back causing shock waves to pass through the rocks. The place under the surface where this happens is called the **focus**; and shock waves radiate out from the focus in all directions. The shock waves first reach the surface directly above the focus, at the **epicentre**. Here they move outward causing the ground surface to move up and down in waves, rather like ripples radiate out across a pond when you throw a stone into the middle. When these surface waves are large, earthquakes can be very destructive, with the greatest destruction usually occurring at the epicentre, reducing outwards. You can use bricks and elastic to model how earthquakes work using the 'Earthquake prediction - when will the earthquake strike?' activity from `http://www.earthlearningidea.com`.

Major earthquakes occur at transform faults (conservative plate margins), like the San Andreas Fault in the USA, where parts of the Earth's crust slide past one another in strike-slip faulting (Figure 5.2). If this slip is slow and steady, earthquakes are uncommon. However, if friction causes one plate to stick against another, pressures build until the fault suddenly fractures in a large earthquake. These are near-surface or **shallow focus earthquakes**.

Shallow focus earthquakes are also common at divergent constructive plate margins, such as beneath Iceland and the East African Rift Valley. Here the tension caused by plates

Figure 5.3: Earthquake damage in Japan - Chuetsu earthquake, 2004.

moving apart results in blocks of crust slipping downwards at normal faults. These shallow focus earthquakes are usually small and not very destructive.

The largest earthquakes occur at transform faults and destructive plate margins. At destructive margins, huge compressive forces move the plates towards one another causing the crustal rocks to fracture along reverse and thrust faults. Since plates are subducting in these areas, earthquakes can occur in the subduction zone at any depth down to 700 km (below this depth, subducting plates begin to melt so can no longer fracture). This is why shallow, **intermediate depth** and **deep focus earthquakes** affect convergent plate margins, and some of these are the largest earthquakes ever recorded.

When loose surface material is shaken by earthquakes, it can ‘liquefy’ and lose all its strength allowing buildings to collapse and shallow slopes to slip as shown in the photo (Figure 5.3). You can see this **liquefaction** process in action yourself using the ‘Quake shake - will my home collapse’ activity at `http://www.earthlearningidea.com`. Earthquakes can also trigger other damaging Earth processes, including landslides and tsunamis.

Tsunamis are series of waves triggered in large bodies of water, such as lakes or oceans, by geological events. When there are sudden movements of rock under the water (or large landslides into the water), the displacement produces waves on the surface. In open water, these waves are low and have little effect, but as they approach land, the base of the waves slows down, causing the height of the wave to rise. Tsunamis can be so devastating because they involve huge volumes of water and cross oceans at more than 800 kilometres per hour. As they reach the coastline the power of the tsunami can drive large volumes of water onto the land with surges measured up to 14 metres high. Since

Figure 5.4: The South East Asian tsunami, 26th December, 2004.

these rush in faster than you can run, many people can be killed, as in the South East Asian Tsunami in December, 2004, which killed more than 300,000 people on coasts all around the Indian Ocean. Tsunamis used to be called tidal waves, but the Japanese word ‘tsunami’ is a better term, since they are not linked to tides at all. See the ‘Tsunami: What controls the speed of a tsunami wave?’ and the ‘A tsunami through the window’ activities at `http://www.earthlearningidea.com`.

Movement of the crust can cause slow gentle effects or catastrophically fast effects, and the same spectrum is seen in volcanic eruptions, which can range from gentle extrusion of lava to devastating blasts of volcanic debris. The main factor controlling the violence of eruptions is the viscosity of the lava: runny lavas can flow gently out of the ground forming sheets of lava and shallow-slope volcanoes, whilst thick slow-flowing lavas are much more explosive and form steeper-sided volcanoes. Magma viscosity is affected by its composition: basaltic, iron-rich magmas have low viscosity whilst intermediate and silica-rich magmas are highly viscous. Viscosity is also affected by the temperature of the lava and whether there is much solid material (as crystals) present. In general, hot, iron-rich magmas with little crystal content flow quickly, whilst cooler, silica-rich magmas containing crystals flow slowly. The significance of this is that basaltic volcanoes, as found at constructive plate margins, and ‘hot spots’ on Earth like Hawaii, produce relatively safe eruptions. So, providing you are careful you can go and watch or photograph these eruptions safely (see Figure 5.5 for an example); the lava sprays into the air as ‘fire fountains’, rains down as liquid and then flows downhill. The volcanic eruptions of intermediate and silicic magma at subduction zones are quite different and cause a range of highly dangerous volcanic processes, producing solid volcanic blocks and huge

Figure 5.5: A basaltic eruption in the Hawaii Volcanoes National Park.

volumes of ash. To simulate changing the viscosity of lava, try the ‘See how they run: investigate why some lavas flow further and more quickly than others’ activity on the `http://www.earthlearningidea.com` website.

The viscous magma can sometimes flow out of steep-sided volcanoes like toothpaste, but more often, it solidifies in the vent so that pressure mounts, eventually triggering a violent eruption. This may be a horizontal blast, like the one that flattened a 600 square kilometre forest of trees like matchsticks at Mount St. Helens in 1980, or a vertical blast, as blasted ash 34 km into the air in the eruption of Mount Pinatubo in the Philippines in 1991.

Volcanic ash itself can pose a hazard. In a thick volcanic ash fall, there is total darkness; ash in the air makes it difficult for people to breathe, particularly those who already have breathing problems. The ash blown high into the atmosphere in major volcanic eruptions (Figure 5.6) can rain down over thousands of square kilometres of land, blanketing towns and agricultural land; near volcanoes it can rain down so thickly that roofs collapse

Figure 5.6: An ash eruption rising into the upper atmosphere - Redoubt Volcano, Alaska, 1990.

and elsewhere it can cover and kill crops. Ash and volcanic gas from the Mount Pinatubo eruption reached the upper atmosphere and had global effects, producing beautiful sunsets and causing the Earth to cool by 0.4°C that year.

If volcanic ash, having fallen on the sides of the volcano, becomes mixed with large amounts of water, from a crater lake, melting ice or snow, or from the thunderstorms that are frequently triggered by volcanic eruptions, the results can be a devastating mudflow of volcanic debris called a lahar (see Figures 5.7 and 5.8). Lahars are like liquid concrete, flowing down valleys at tens of kilometres per hour carrying ash and boulders and, if large enough, spreading out on the plains below, before becoming solid. Lahars can be huge: one formed a wall of mud 140 metres high and another covered an area of more than 300 square kilometres.

Lahars are so dangerous because, if not monitored carefully, they can arrive unexpectedly and with devastating power, tens of kilometres from the volcanic vent. This happened with the lahars from the Nevado del Ruiz volcano that buried the town of Armero in Columbia in 1985, killing more than 20,000 people. Although geologists and other experts had warned the authorities of the danger beforehand, city officials downplayed the warnings and, the night before the eruption, the mayor had told the inhabitants that there was nothing to fear.

Figure 5.7: A lahar from the crater of Mount St. Helens.

Figure 5.8: A bus damaged by a lahar flow from Mount St. Helens.

Figure 5.9: Pyroclastic flows (nueées ardentes) flowing down the slopes of Mayon in the Philippines during the 1984 eruption.

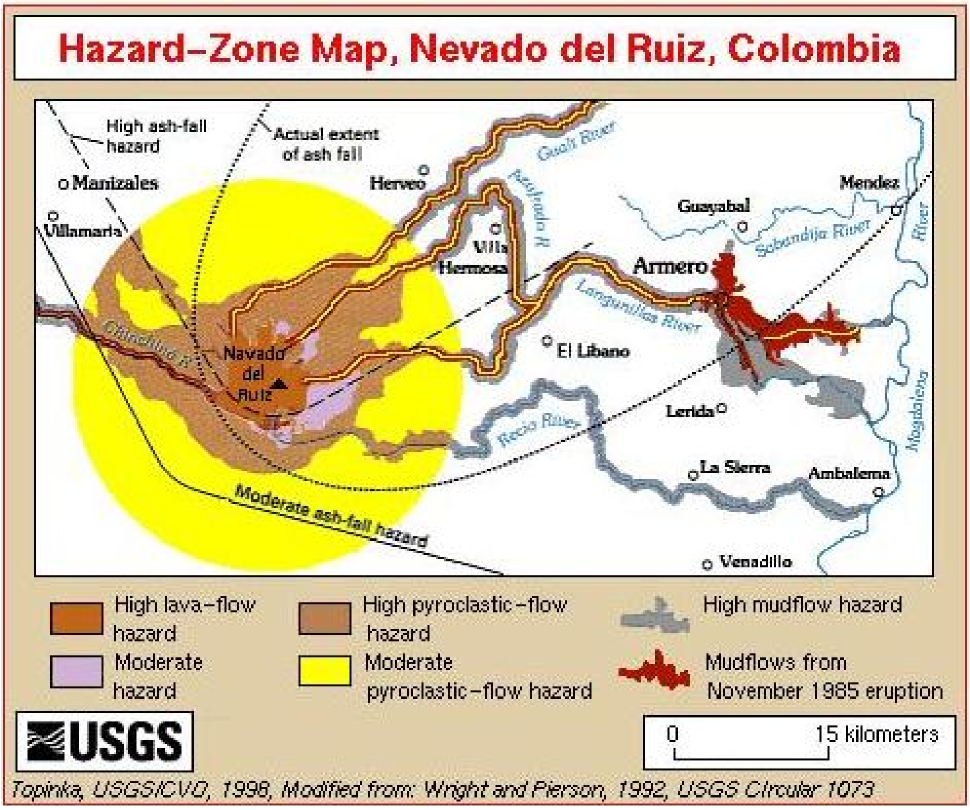


Figure 5.10: A hazard zone map of the Nevado del Ruiz volcano showing volcanic hazards, including the high mudflow (lahar) hazard areas (which included Armero) and pyroclastic flow (nuée ardente) risk areas; the map was produced after the Armero disaster.

Destructive volcanoes with intermediate and silica-rich magmas not only erupt columns of ash into the air, but the column may collapse and flow sideways as red hot (up to 1000°C) clouds of ash and gas called **nuées ardentes** (glowing clouds) or **pyroclastic flows**. Since these clouds of ash in air are denser than the surrounding air, they flow downhill as density currents at speeds of hundreds of kilometres per hour, incinerating anything in their paths (Figure 5.9). They tend to become funnelled down valleys and spread out on the plains beneath, rather like lahars, but much hotter and faster, and can even flow across water. The hazard map of Nevado del Ruiz (Figure 5.10) shows potentially hazardous pyroclastic flow paths as well as lahar flow paths.

The landslide at Mount St Helens which triggered the 1980 eruption occurred after months of activity had built a huge bulge on the side of the mountain. An earthquake triggered the largest landslide in recorded history at the steep edge of the bulge. This released the lateral blast that was followed by the full eruption. Although this landslide was an unusual event, most other major landslides were triggered by earthquakes too, although some were also triggered by storms.

Landslides are the result of the collapse of unstable slopes under gravity. The stability of slopes depends upon how steep they are, the weaknesses in the material (from faults,

Figure 5.11: Landslide triggered by the El Salvador earthquake in 2001.

joints, bedding and other slippage surfaces) and the pressure of the water in the pore spaces (the **pore water pressure**). Slopes are more prone to fail if they have been steepened by human activity or by erosion of material from the foot of the slope, if weaknesses have been attacked by weathering, or if they become waterlogged during storms. In these circumstances, a small amount of extra stress can cause slopes to fail and collapse. Near vertical slopes can collapse by toppling, but most fail by simply sliding downwards, usually breaking up into debris, large and small. Such debris can be carried a long way, particularly if there is enough water for it to become a slurry. **Mudflows** and **debris flows** usually begin as landslides; debris flows carry boulders whilst mudflows are mostly formed of finer material, but both can be devastating, as shown in Figure 5.11. See the 'Landslide through the window' 'thought experiment' and the 'Sandcastles and slopes: what makes sandcastles and slopes collapse?' activity at `http://www.earthlearningidea.com`.

Catastrophic Earth processes only become hazards when they affect people, as they clearly did in the 2001 El Salvador earthquake (Figures 5.1 and 5.11), so if an Earth process has a devastating effect on a wilderness area, it is not classed as a hazard because there is no risk to humans. The amount of risk caused by geological hazards, or **geohazards**, often depends upon the types of human activities involved, whilst people often increase their risk by their behaviour. Humans construct settlements and large scale building projects in geologically hazardous areas for a wide variety of reasons, including good access, good agriculture, or lack of other available land. Risk is increased by population density; the more people in a vulnerable area the greater the loss of life that can result.

Geohazard risk is reduced by taking a series of actions: first the risk should be assessed and evaluated; then if there has to be construction in risky areas, buildings and other civil engineering projects should be built as safely as possible; then mechanisms should be put in place to monitor and forecast future potential hazards; finally plans should be made to protect the human population during and after a geohazardous event.

The first stage of preparing for geohazards is to assess the hazard and possibly to prepare a geohazard map, like that in Figure 5.10. It is fairly easy to assess tsunami risk - any low-lying area in a tsunami-prone region is in danger; it is relatively easy to map volcanic risks, since the presence of volcanic materials from the recent past is good evidence that they may be deposited again, and there may even be historical evidence of past events. Mapping landslide danger is more difficult, since any steep slope may be prone to landslides, but techniques involving careful examination of rocks and evaluation of earthquake potential can be effective in producing landslide geohazard maps. It is, however, very difficult to produce good local earthquake geohazard maps, since so many variables are involved, including the intensity of the earthquake and the strength of the subsurface rocks.

Figure 5.12: Buildings that did not resist the Mexico City earthquake of 1985.

If building has to take place in geohazardous areas, then the constructions should be hazard-resistant. Many countries in areas prone to geohazards have building codes, so that in earthquake-prone areas, buildings are constructed to be able to flex and not fracture during earthquakes, they are given sturdy foundations and use strong building materials. Older buildings can be 'retrofitted' to make them more earthquake-resistant - the objective is not for buildings to remain completely undamaged by a major earthquake, but to to make them resistant enough for their inhabitants to survive. Unfortunately in many developing countries, building codes are not enforced for a range of reasons, including expense and lack of suitable infrastructure, so much construction in developing regions may be affected by geohazards in the future (as in Figure 5.12). In tsunami-prone areas, buildings of concrete are more likely to survive than buildings made of local materials. The safest way of constructing buildings safe from landslides is not to build them on or beneath slopes. Volcanic eruptions of most violent volcanoes are infrequent, and volcanic

Figure 5.13: Seismic monitoring of volcanic activity.

areas often have fertile soils and may be attractive to tourists, so that much building has taken place on potentially hazardous volcanic slopes. The most effective way of reducing risks in these areas is to monitor and prepare.

Volcanoes can be monitored by a wide variety of methods. Nowadays, some volcanoes are routinely monitored remotely by satellites that can identify temperature changes, emission of sulfur dioxide or ash clouds, or small changes in shape of the surface of the volcano. Meanwhile ground monitoring techniques that have been developed over many years include seismic monitoring (many eruptions have increased small earthquake activity before eruption and some seismic traces are characteristic of lava movement at depth); monitoring of the shape of the volcano (by tiltmeters, that detect changes in the slopes of surfaces); and by measuring the changes in altitude and distance across key parts of the volcano, to spot the development of volcanic bulges before eruptions. Try making your own tiltmeter from, 'When will it blow?: predicting eruptions' at http://www.earthlearningidea.com. On many volcanoes the emission of volcanic gases is monitored

Figure 5.14: A GPS (global satellite positioning) remote volcano monitoring station, monitoring deformation of the slopes of a volcano.

for any changes in gas composition that may occur before eruption, whilst small scale changes in gravity and magnetism may also be used to predict eruptions. Unfortunately, all the equipment needed for thorough volcano monitoring is very expensive, so that, whilst many volcanoes in the USA are closely monitored, many in the developing world are not. Eruption risk to populations is much higher in volcanic regions that have less effective monitoring systems.

Scientists have been investigating earthquake prediction for many years and have shown that, while it is impossible to predict earthquakes (the exact time and place where they will occur) it may be possible to forecast earthquakes, suggesting the probability that an earthquake will occur at a given place at a given time. These forecasts have been based on a number of methods including:

- **seismic gaps**: when faults are under plate tectonic pressure, some parts of faults slip gently, whilst others are 'locked'. The locked parts are seismic gaps, where earthquakes have been recorded on either side, but not in the middle; the next big earthquake is most likely in this seismic gap area. Figure 5.15 shows how the ground surface moved in the Izmit earthquake in Turkey in 1999. Other major earthquakes have happened along the fault to the east, so the next large earthquake is likely to be in the seismic gap to the west; this happens to be beneath the city of Istanbul.
- **foreshocks**: many major earthquakes have smaller foreshocks beforehand, however, many small foreshock-like earthquakes can occur along a fault without a major earthquake following them.

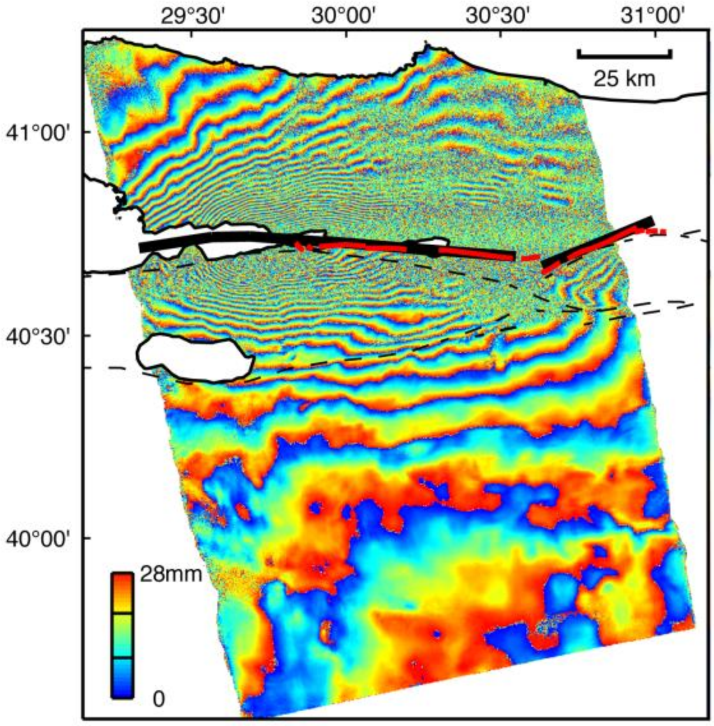


Figure 5.15: An interferogram of the Izmit earthquake, Turkey, 1999, produced by comparing satellite data from before and after the earthquake. Most movement of the ground surface occurred where the colour bands are closest together and this shows the position of the fault very clearly.

- ground deformation: deformation of the ground near a fault, measured using stress gauges, tiltmeters or by surveying, may provide signs of a future earthquake.
- groundwater variations: as pressure increases in the rocks around a fault, cracks may open or close causing the level of the water table in wells or boreholes to change, suggesting a future earthquake.
- radon gas: the cracking of rocks before an earthquake may release radon gas into the groundwater, which can be detected.
- geomagnetic and geoelectric changes: changes in both local magnetism and local electrical resistance have been recorded just before an earthquake struck.
- earthquake lights: there have been reports of ‘earthquake lights’ before earthquakes, flashes of red and blue light in the sky that may be caused by quartz crystals fracturing under stress.
- animal behaviour: there have been accounts of some animals like dogs and cats behaving strangely before earthquakes, but it has not been possible so far to use this in effective earthquake forecasting.

None of these methods has yet proved to be scientifically successful in reliably forecasting earthquakes. Meanwhile, scientists have to be very careful not to forecast an earthquake that doesn't happen, since an inaccurate forecast can be very costly and the population is less likely to take notice of future forecasts. The work of seeking reliable earthquake-forecasting techniques is likely to continue for many years to come.

Landslides can be fast or slow-moving. There is no time to monitor fast-moving events, but landslides that creep slowly and threaten buildings or other constructions such as roads, can be monitored by instruments to detect movement, ground vibration, groundwater changes, or rainfall. However, this is expensive, and is only usually possible in well-developed countries.

A range of techniques is available to reduce the effects of creeping landslides, including improving drainage, planting vegetation to bind the material with roots and remove water, and anchoring the toe of slips with heavy masses of material or stone-filled **gabion** baskets. Rockfall hazards in steeper areas can also be reduced by using **rock bolts** to tie down looser sections, by covering steep surfaces with mesh **geotextiles** or concrete blankets (**shotcrete**) and by building fences and ditches to catch debris. Again, these remediation techniques are usually only possible in well-developed countries.

The final stage of tackling geohazard risk, after assessing geohazard impact, controlling building construction, and using prediction/monitoring methods, is to develop plans to protect the population during and after an event. Such plans will differ, depending on the type of event and its likely scale. However, most plans have in common: the training of the emergency services, the education of the population on what to do and when, the use of early warning systems where possible, the development of evacuation plans, procedures to maintain essential services, and strategies to call in extra help and resources if necessary. See the 'Surviving an earthquake' activity at `http://www.earthlearningidea.com`.

5.2 Human impacts on climate change

Media reports often link all sorts of natural disasters to climate change but, although climate change will have long term effects on the Earth, it is not directly responsible for short term changes like those in the weather or sudden geohazard events.

Nevertheless, as shown in Section 3.3 of this book, climate change could have dramatic effects in the future. Global warming could cause marked temperature rises and increases in drought in some parts of the Earth, linked surprisingly to cooling in others. Global climate belts would tend to move towards the poles and the world's weather patterns would probably become more stormy. If the warming caused major melting of the continental ice sheets (on Greenland and Antarctica), global sea levels would rise significantly. Meanwhile the water in the warming oceans would also expand, causing many low-lying areas, including many of the world's major cities, to be prone to large-scale flooding during storms.

For these reasons, many scientists and an increasing number of politicians and other influential people across the world are arguing that the human population should do all

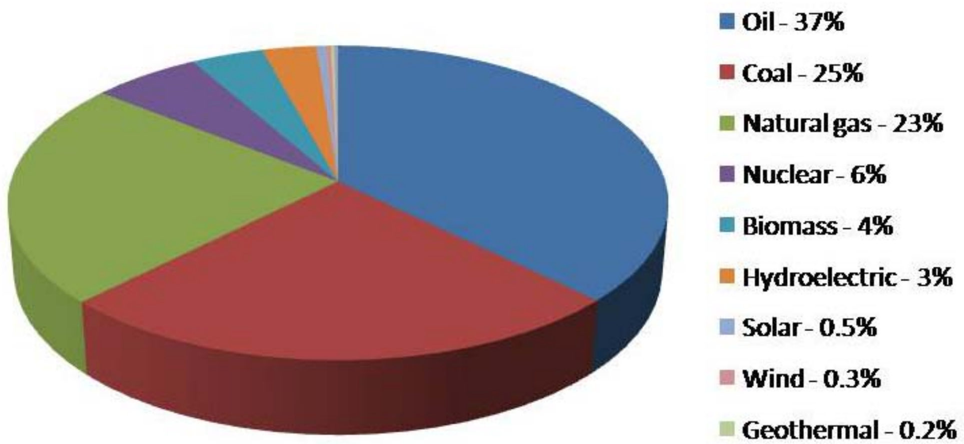


Figure 5.16: The sources of fuel used in current world energy consumption.

it can to reduce the effects of climate change. One of the main causes seems to be the increasing amount of carbon dioxide (and other 'greenhouse gases') in the atmosphere and their 'greenhouse effect'. Even though enormous amounts of carbon are cycled through the carbon cycle and the Earth's atmosphere each year, through such processes as photosynthesis in plants and respiration in all organisms, the amount of carbon dioxide in the atmosphere in the recent geological past had stayed fairly stable until the beginning of the Industrial Revolution. As more and more fossil fuel has been burnt since this time, the carbon dioxide content of the atmosphere has increased, so that now about 100 times more carbon dioxide is released into the atmosphere each year by burning fossil fuels than is released by natural volcanic emissions.

The fossil fuels, coal, oil and natural gas, together are called hydrocarbons. When the carbon in them burns, it combines with oxygen from the atmosphere to form carbon dioxide. As the atomic mass of oxygen (16) is greater than that of carbon (12), and each carbon atom combines with two oxygen atoms to make CO_2, the mass of the carbon dioxide produced by burning is greater than the mass of the original carbon. Even natural gas, the most efficient of the fossil fuels, emits more than its weight of carbon dioxide on burning.

Currently more than 80% of the power used on Earth comes from the burning of fossil fuels (Figure 5.16), so there will be no easy way to reduce carbon emissions. Nevertheless three different methods are being used to reduce the amount of carbon dioxide being released to the atmosphere:

- generate more power from non-hydrocarbon fuel sources, to reduce the burning of hydrocarbons;
- reduce the amount of power needed, by using fuel more efficiently;

Figure 5.17: A windfarm in Ireland.

Figure 5.18: Solar panels being used in Mallorca.

- burn hydrocarbons, but then trap the carbon dioxide formed and store it in old exhausted oil and gas fields.

Figure 5.16 shows how difficult it is going to be to generate a lot more energy from non-hydrocarbon sources. We can't easily increase **biofuel** production, as this would mean growing and burning more trees; biofuels are usually grown on land used to grow crops for human consumption, so production from these is not likely to increase greatly. Increasing power production from hydroelectricity would mean building more dams and reservoirs, which is not possible in dryer or low-lying countries. For these reasons, most effort is being focused on nuclear, solar and wind power generation. Nuclear power is being strongly developed in some countries and being considered by others, despite the problems of nuclear waste disposal and potential large scale nuclear disaster. Wind, solar and geothermal power supplies are also being developed, but these are starting from such low percentages that they won't make a great impact on global power supplies for some time.

Many countries are developing onshore and offshore **windfarms** of clusters of **wind turbines**. Meanwhile buildings in some regions are being fitted with solar panels to contribute to the energy needed by the building, whilst other building projects are using the 'geothermal energy' supplied by '**heat engines**'. These draw in heat from the surrounding ground (ground-source heat engines) or air (air-source heat engines) which is then used for heating the building. In warm summers, heat can be returned to the ground by reversing the heat engines to provide air conditioning. Most of the 'geothermal energy' used by ground-source heat engines, and all the air-source heat engine energy, is actually solar energy from the sun, and so is not 'geothermal' at all. Proper 'geothermal energy' is only available in 'hot spot' areas of the Earth, like Iceland or New Zealand, or where it has been trapped in deep underground water supplies over many thousands of years, as in parts of France.

One of the factors likely to be contributing to the increase of carbon dioxide in the atmosphere is the cutting down of forests, particularly in equatorial regions. Trees absorb and store carbon dioxide through photosynthesis, but can no longer do this if they have been felled. This is why there are global concerns over deforestation, particularly of the

Amazon rain forests. This is also why new trees are being planted in many parts of the world, sometimes as part of '**carbon trading**' where an organisation might plant new trees to offset its energy consumption from fossil fuels.

There are also major global attempts to reduce fuel consumption: by making engines, large and small, more efficient; by developing more efficient industrial processes; by reducing heat losses from older buildings; and by constructing new buildings that are more energy-efficient. In these ways, organisations and individuals are trying to 'reduce their **carbon footprint**'.

The new technology of removing carbon dioxide generated by burning fossil fuels and pumping it into abandoned oil and gas fields is still experimental. This is called '**carbon sequestration**' or '**carbon capture**' and is part of the '**clean coal technology**' being discussed as a method of using coal to produce energy without polluting the environment and adding greenhouse gases to the atmosphere. If this does become successful it is likely to be many years before it is available for large scale use.

For all the reasons described above, many countries are currently considering the 'nuclear option' as a way of supplying substantial amounts of power, and so reducing the consumption of fossil fuels, while other methods of power generation are being developed. See the 'Power through the window' 'thought experiment' activity at `http://www.earthlearningidea.com` to think about how energy production might affect your local environment.

5.3 Great fossil finds

The media often report important fossil finds, but these are only really 'great fossil finds' if they provide new evidence for life on Earth in the past. Such finds normally fall into four categories:

- exceptional preservation - the unusual circumstances where groups of fossils are so well preserved that their soft parts and living relationships can be studied;
- 'missing link' fossils - which show how some groups of organisms are linked to others;
- complex fossil skeletons - which, when re-assembled, show the mode of life of individual animals;
- hominid finds - the rare finds that help us to investigate human evolution.

One of the most famous examples of exceptional preservation is the Burgess Shale found high in the Rocky Mountains in Canada. Here, during Cambrian times (about 500 million years ago), organisms that lived in a shallow sea were swept off the edge of an undersea cliff, probably during storms, and were preserved in mud at the foot of the cliff. Not only was the preservation exceptional, in that the finest details of the soft parts of the animals are often preserved, but also a wide variety of animals has been found, many completely unlike animals found on Earth today (see Figure 5.20). Evolutionary scientists have hotly

Figure 5.19: A beautifully preserved *Archaeopteryx* fossil, with a model in the foreground.

Figure 5.20: One of the strange animals found exceptionally preserved in the 505 million year old Cambrian Burgess Shale in Canada.

debated whether these strange animals are related to modern animal groups or not and what this means for the evolutionary story - and the debate continues. This debate would not have been possible if the unusual fossilisation circumstances had not preserved the specimens so completely.

Examples of rock sequences with exceptional preservation like this are called **lagerstätten** and only about 50 examples of lagerstätten are known from the whole geological record. However, these have given scientists unique 'windows' into the variety and detail of life at key times in the Earth's past.

Another example of lagerstätten is the Jurassic Solenhofen Limestone in Germany (about 150 million years old) in which fossils of *Archaeopteryx* have been found (see Figure 5.19). As in other lagerstätten, the *Archaeopteryx* fossils are beautifully preserved and it is clear that they not only had small teeth, like reptiles, but feathers like birds as well.

Before the finding of *Archaeopteryx* scientists had debated long and hard how birds had evolved. The *Archaeopteryx* specimens, with many features similar to dinosaurs (types of reptiles), but also with wings and feathers, showed how birds evolved from reptiles and so provide a 'missing link' in evolutionary history.

Another 'missing link' find has recently been reported. The headline in a UK newspaper read '***Fossil Ida: Extraordinary find is 'missing link' in human evolution'*** (the *Guardian* newspaper, 19 May 2009). The article continued, 'Scientists have discovered an exquisitely preserved ancient primate fossil that they believe forms a crucial "missing link" between our own evolutionary branch of life and the rest of the animal kingdom.' The newspaper story described the fossil which, very unusually, was 95% complete, with the hair, and even the last meal of the small animal preserved. It was a young female about 6 to 9 months old that may just have left its mother, and was found in sediments deposited in a volcanic lake 47 million years ago. It forms a 'missing link' between early small **primate** animals and the group that later evolved into monkeys, apes and eventually, humans.

Some media reports and many cinema films/movies suggest that the skeletons of large animals are often found intact in sedimentary rock layers. This only happens in really exceptional circumstances, as with 'Ida' above. Much more common is the finding of separate bones, like the one being excavated in Figure 5.21. The bones are usually separated because, after the animal died many things could happen before the bones were buried. Scavenging animals may have pulled the bones apart and chewed up the smaller bones, the animal may have rotted so that the skeleton fell apart, or it may have been swept away and broken up in a river or the sea. When groups of bones are found together, geoscientists usually try to reconstruct the animal to show what it was like when it was living. When this was first done, many mistakes were made. In the famous case of *Iguanadon*, early reconstructions showed a 'spike' on the nose, but it was later found to be one of the two thumb spikes.

When skeletons are reconstructed today, evidence is used from several skeletons, from the size and shape of the bones including the scars left by muscles, from how similar modern animals live, and from features like footprints that show how the animal moved. So, modern skeleton reconstructions are much more accurate, and realistic working models and animations can be made, like those in the 'Walking with dinosaurs' TV programmes and exhibition. Most of the details of these models and animations are as accurate as they can be, although we are never likely to know the exact colours of the skins, the sounds the animals made, or the detailed ways in which they lived (as in Figure 5.22).

The search for early human fossils is even more difficult, since they were much less common than many dinosaur groups and they usually lived on land well away from environments where they might be fossilised. So scientists and media reports are often very excited by very small human-related finds.

When a skeleton was found in rocks more than 3 million years old in Ethiopia, with parts of nearly all the major bones preserved, there was huge excitement. This was a fossil of an early type of **hominid** called *Australopithecus* on the evolutionary line that eventually produced *Homo sapiens*, humankind. This fossil was soon christened 'Lucy' and you can read the exciting story of the find on the internet. 'Lucy' was so important because she had the size and shape of a chimpanzee, but also had many characteristics of modern humans.

Figure 5.21: A dinosaur excavation.

Figure 5.22: A dinosaur reconstruction showing how they might have lived.

There was more excitement a few years later when footprints of *Australopithecus* were found in a bed of 3.6 million year old volcanic ash in Tanzania, Africa. Since igneous rocks like volcanic ash contain radioactive elements, we can date them quite precisely using radiometric techniques. The footprints are of three individual hominids, who had walked across the layer of ash in the same direction. They show that the Australopithecines walked upright (unlike chimpanzees) and computer simulations show that they were walking along at about 3.5 kilometres per hour, strolling speed.

Even though detailed evidence of hominid evolution like this is very rarely found, nowadays geoscientists have been able to build up a good picture of how humans have evolved. We can also use evidence from the DNA of modern primate groups to support the evolutionary story and to build an even more complete picture of how *Homo sapiens* evolved to be like we are today.

The more we study the rocks of the Earth's surface, the more fossil evidence we find of life in the past and how it contributed to the evolving environments on Earth. As more fossils are found and reported in the media in the future, more detail will be added to the jigsaw picture of life on Earth.

5.4 Planning, quarrying and landfill

The most commonly reported geoscience-related issues in local newspapers and news reports are usually about quarrying and **landfill**, and the planning related to them.

Figure 5.23: The bones of the more than three million year old *Australopithecus* skeleton 'Lucy' found in Ethiopia, Africa.

Figure 5.24: A reconstruction of the 'Lucy' *Australopithecus* skeleton.

Quarrying produces the raw materials needed for construction. Without quarry products, no building could take place. Indeed, nearly all the material used for the buildings around you came from the ground.

The materials produced by quarrying fall into five main categories:

- **aggregate** - crushed rock (e.g. limestone, sandstone, basalt) or sand and gravel from gravel pits, used to add to concrete, for foundations and for railways; some fine aggregates are also used to make building blocks that look like building stones;
- limestone - used to make cement, for the chemical and fertiliser industries and in **smelting** iron ore;
- brick clay - from brick pits, used to make bricks and roofing tiles;

Figure 5.25: A working aggregate-producing quarry on Sifnos, Greece.

- building stone - nowadays used mainly for ornamental **facing stones** for high prestige buildings (in thin slabs attached to the walls of the buildings) or as flooring, and for memorials, statues, and fireplaces, but also for repairs to old stone-built buildings, walls and pathways;
- specialist products - such as china clay, pottery clay, silica sand for glass-making; gypsum to make plaster, and slates for roofing older buildings.

This list shows that 'quarrying' normally includes sand and gravel pits, but does not include large opencast mines used for coal, copper or iron ore extraction. Neither does it cover deep mines for coal and ore minerals. Since quarry products are bulky and heavy, they are normally extracted as close to the site where they are being used as possible, to minimise transport costs. Thus many small abandoned quarries and pits are found near older built up areas. Nowadays, because it is difficult to get planning permission to excavate new quarries, the trend is for larger quarries to be developed near transport links, from where the materials can be transported to where they are needed. Sometimes superquarries have been developed on the coast, from where the products can easily be transported worldwide. The exception to this is the ornamental stone industry where today, it is often cheaper to import stone from large exporters abroad, than to quarry it locally.

When new quarries or gravel pits are being planned, or older sites are being extended, the planning application should cover the following issues:

- the size and shape of the development and the likely duration of the quarrying;

- noise and vibration - the sounds of explosive blasting and of heavy machinery should be minimised - earth banks (**bunds**) may be built and trees planted to reduce noise;
- dust and air quality - dust pollution should be minimised by, for example, spraying dirt roads with water during dry periods and washing vehicles regularly;
- water supplies and groundwater - boreholes are often drilled and monitored to check on groundwater flow directions and ensure that groundwater supplying water to surrounding areas does not become polluted - meanwhile water used on site needs to be stored, cleaned and recycled;
- landscape - quarries should be sited to minimise impact on local views - banks and trees may be positioned to hide the signs of quarrying;
- natural and cultural heritage - the local wildlife and areas of historical interest should be conserved;
- traffic impact - the local road system may need upgrading to deal with quarry traffic;
- waste - proper waste management systems should be in place;
- environmental management systems - the local environment during and after quarrying will need to be managed, including the development of a post-quarrying environmental plan.

If the planning application is opposed by local groups of people or national bodies, the planning proposal may be taken to a public inquiry. You can work out how the pros and cons of quarry proposal would be debated yourself, by role-playing the 'Limestone inquiry: 21st century' on the JESEI website at: `http://www.esta-uk.net/jesei/index2.htm` and thinking about how a quarry might affect your area through the 'Quarry through the window' activity at `http://www.earthlearningidea.com`.

When quarries, brick pits or gravel pits are closed, the post-quarrying environmental plan is likely either to convert the area to a public amenity or to use it for waste disposal. Quarries less suitable for waste disposal or important for amenity purposes, can be landscaped to form nature reserves or country parks; the Eden Project in Cornwall (Figure 5.26) has transformed an abandoned china clay pit into one 'of the UK's top gardens and conservation tourist attractions' according to its website. Many country parks and nature reserves in quarries conserve rock faces for educational and scientific use and these may be protected by local planning laws.

Most waste material across the world, is disposed of in landfill sites. These are often old quarries but, in countries where there is a shortage of sites, other depressions in the landscape are used as well.

The old method of dealing with waste, when little was being produced by human populations, was the "**dilute and disperse**" method, in which the poisonous fluids produced by decaying waste were allowed to disperse in the rocks, diluted by rainfall. As more and more waste was produced, environmental pollution increased, so the policy was changed to

Figure 5.26: The Eden 'biome' Project in Cornwall, UK, in an old china clay pit.

"**concentrate and contain**", where the waste was carefully controlled and fluids were not allowed to leak into the surrounding rocks. Today's policy is "**integrated waste management**" with its motto, "reduce, reuse, recycle", where as much waste as possible is reused, some is processed and recycled, and the remainder is crushed into the smallest volume possible and disposed of in carefully controlled landfill sites.

Three broad types of waste are generally recognised:

- 'inert' waste - such as rubble from demolished buildings that is largely unreactive;
- domestic, commercial and industrial waste - the rubbish/trash disposed of by households, business and industry;
- hazardous waste - dangerous waste products such as toxic chemicals, carcinogenic (cancer-forming) waste, inflammable liquids and radioactive waste.

When rainfall gets into waste, it becomes contaminated with decaying waste materials to form nasty liquids called **leachate**. Waste decay also produces landfill gases such as methane. Thus one of the most important controls on where different sorts of waste can be disposed, is the permeability of the rocks in which they are to be placed. If the rock is permeable, leachate and landfill gases can leak into the rock through the pore spaces. The leachate may then pollute groundwater and later reach the environment through springs and marshes or the local water supply. Meanwhile, the methane can build up in hollows like caves and cellars, and has been known to cause explosions.

Since 'inert' waste is largely unreactive, it can be disposed of in permeable rocks like limestone or sandstone quarries. However, decaying domestic, commercial and industrial waste produces both leachate and methane and has to be disposed of in impermeable sites. In such sites, a network of pipes is laid along the bottom to collect the leachate so that it can be extracted, processed and disposed of safely, whist a series of vertical pipes vent the methane to the surface or collect the methane and use it to generate electricity (since methane is a potent 'greenhouse gas' it is better to collect and use it than to vent it to the atmosphere). When the sites are full, they have to be carefully capped with impermeable material to stop rainwater getting in and causing the leachate to overflow.

Figure 5.27: A landfill site in Hawaii, USA. The base of the old quarry and the sloping sides have been covered with a black plastic landfill liner (membrane) to ensure that fluids don't leak into the surrounding rock; this is then covered by gravel for protection.

Since clay is impermeable, abandoned brick pits are important waste disposal sites. If quarries in permeable rocks have to be used, then an impermeable plastic **landfill membrane** is laid across the floor and walls of the site, to contain the fluids produced (Figure 5.27). Boreholes are drilled nearby so that the groundwater can be monitored for pollution. These are expensive methods and so permeable sites are only used when impermeable options are not available.

Even more care has to be taken with the disposal of hazardous waste. Some is carefully incinerated whilst other types are chemically treated or mixed with cement and buried in highly impermeable sites. There is still much debate over the disposal of radioactive waste. Low level radioactive wastes are currently being used as landfill in very carefully chosen and controlled sites. Currently, high level radioactive wastes are being turned into a form of glass and stored under water, while scientists in most waste-producing countries search for solutions to their long term disposal.

Since the disposal of waste can produce unpleasant by-products as well as affecting the local environment, it is not surprising that there are often local news reports on waste disposal plans. However, the enormous volumes of waste that humans produce, particularly in more developed countries, have to be disposed of safely somewhere, and so environmental debates on waste disposal are likely to continue for ever.

Chapter 6

Understanding what geologists do: how geologists use investigational skills in their work today

6.1 What geologists do

Figure 6.1: Geologists at work, examining cores from a borehole.

If you were employed as a geologist, what would you do? The answer would probably depend on where you live. In developing countries, most geologists are employed in prospecting for and extracting raw materials. These include fuels such as oil, gas and coal, the materials needed for construction and industry (provided by mining and quarrying), and groundwater supplies. In more developed countries, the balance is different, and most geologists are employed in environmental protection, helping to clear up environments damaged by the extraction of raw materials in the past, while ensuring that extraction and waste disposal today minimise environmental damage; environmental geologists also contribute to the climate change debate. Meanwhile, geologists are widely employed in geotechnical work, ensuring buildings have proper foundations and roads and railways are safely-built.

Many countries also have their own government-run Geological Surveys, employing geologists to build up national databases of geological information and providing expertise to industries involved in geologically-related activity. Geological Surveys across the world provide maps, geological publications and other data to inform government, industry and the public and many also provide educational support. The 'One geology' initiative, launched during the 'International Year of Planet Earth' in 2008, is combining the geological maps produced by Geological Surveys around the world into one global geological map, see `http://www.onegeology.org/`; you should be able to find the geology of your country shown there. Meanwhile many universities across the world have departments of Geology, Geoscience or Earth Science, where geologists carry out academic research and teach future geologists.

If you want to become a geologist, you will need a university degree in a geoscience subject. You may also need extra training or a higher degree. Although many people with geoscience degrees work as geologists, others are employed in a wide range of activities, from business to journalism, to teaching. There are also technical opportunities in geologically-related industries for people with non-university qualifications. Worldwide, geological employment tends to fluctuate, with large numbers of geologists being employed in global 'boom' periods and fewer geological jobs when global industry slows down. Nevertheless, there will always be a need for geologists, to find the raw materials we need, to contribute to safe building, to record global geological data and to safeguard the environment for the future.

6.2 Oil/gas exploration

Geoscientists who explore for oil and gas need to understand how these hydrocarbons are formed and trapped and how to find the buried **reserves**. Oil and gas provide well over half the global fuel supply today and will be providing major contributions to global power supplies for many years to come. Meanwhile, global oil/gas supplies are dwindling, so the world will need geologists in the oil and gas industries well into the future.

For oil and gas to be trapped underground, five things must happen:

- there must be a **source rock** - most oil comes from mudstones that were laid down as mud in ancient seas, containing lots of organic material, usually from the microscopic plants in dead plankton; these muds also produce some natural gas, but most natural gas comes from the source rock coal (which formed from plant debris preserved in ancient swamp deposits);
- the source rock must have been **heated enough** for the organic material to be broken down to release the oil and gas, and compressed to squeeze out the hydrocarbons;
- there must be a **reservoir rock** - reservoir rocks contain the tiny pore spaces that can collect the oil or gas, they are porous (with maybe 10% - 20% pore space) and permeable (so that the fluids can flow through);
- the reservoir rock must have a **cap rock** that seals the hydrocarbons in - the cap rock is often an impermeable clay, but may be a salt deposit or an impermeable clay seal along a fault;

Figure 6.2: A drilling rig used for oil/gas exploration in the North Sea.

- the rocks must form a **trap** that seals in the oil/gas like a bubble (spread through the pore spaces in the reservoir rock); examples of common traps are shown in Figure 6.3.

When an oil or gas reservoir has formed, an organic-rich source rock will have been deposited and will have been heated and compressed, possibly during a mountain-building episode. Oil/gas is less dense than the water that most sedimentary rocks contain, and so flows upwards from the source rock through the water in the pore spaces into a porous and permeable reservoir rock (sometimes though, the oil/gas is squeezed sideways or even downwards). If the reservoir rock has been sealed by a cap rock and formed into the right trap shape, the oil and gas will be trapped. We can then find and extract the oil/gas by drilling boreholes into the reservoir rock. Try modeling your own oil and gas field and borehole through, 'Trapped: why can't oil and gas escape from their underground prison', at `http://www.earthlearningidea.com`.

In oil and gasfield areas, the rock sequence of the region is usually well known from other nearby boreholes, so geologists will already think that there is likely to be a source rock in the area, with a reservoir rock above, possibly capped by a cap rock. The hydrocarbon exploration team must therefore find a trap and drill into it to see if it contains oil/gas.

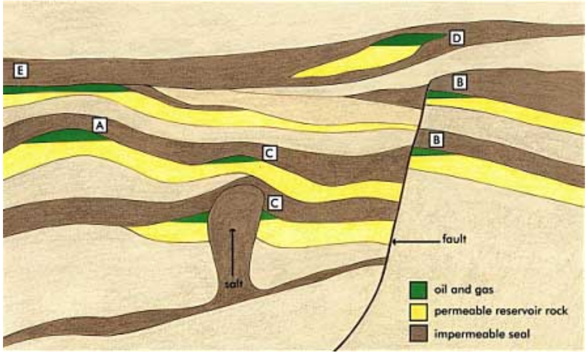


Figure 6.3: Different types of oil and gas traps: A - an upfold (anticlinal) trap; B - fault traps; C - traps caused by a rising salt dome; D - a trap caused by a body of coarser porous sediment in finer impermeable sediment; E - an unconformity trap.

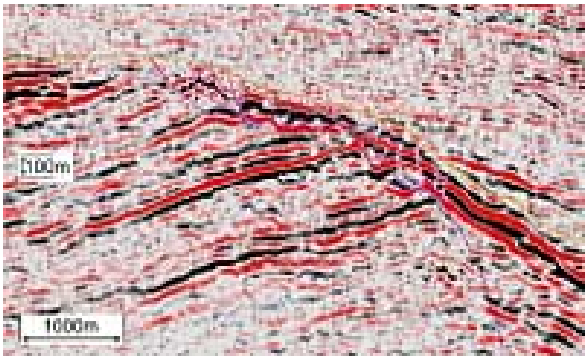


Figure 6.4: A seismic cross section, showing sedimentary beds that dip to the left cut by an unconformity surface; if the dipping sedimentary rocks have alternating reservoir and cap rocks, and if the rock above the unconformity is a cap rock, oil/gas may be trapped in the reservoir rocks.

First, geophysicists will run a series of **geophysical surveys**, such as gravity and magnetic surveys which might suggest areas where a trap may have been formed, as in Figure 6.3. In likely areas they then run **seismic surveys** where shock waves are reflected from the rock layers below the surface, showing a cross section of the geology, as in Figure 6.4. Modern geophysical surveys using the latest technology can reveal the shape and character of the geology beneath the surface very clearly, but they cannot show if a trap contains hydrocarbons. The only way to test whether a potential trap contains oil/gas is to drill a **well** (Figure 6.2).

During the drilling of an **exploration well**, the job of the geologist is crucial, since drilling is vastly expensive and needs to be run as efficiently as possible. Most drilling is done using drill bits that ‘chew up’ the rock into tiny chips, so that the geologist has to interpret the geology from these chips. However, if the geologist needs more information about the rock sequence, a hollow drill bit is used, producing cylindrical **cores** of rock (although this is even more expensive). The geologist will examine the microfossils from the chips and cores to find out where in the geological sequence the drill bit is drilling. If the borehole has not yet reached, or is drilling in, the reservoir rock sequence, it should keep drilling. If it is below the likely sequence, the borehole should be abandoned as the well is ‘dry’ and oil/gas has not been found. The rock chips are used to give other details of the rock as well, such as its permeability, whilst other sensors test for oil or gas.

When the borehole has been completed, it is geophysically surveyed by lowering sensors down the hole in ‘**downhole logging**’. Even if the hole is a dry one, it may give details helpful to interpreting the geology in the next hole to be drilled. Since geologists decide where holes are to be drilled and when they should be abandoned, their decisions are vital to successful hydrocarbon prospecting.

When an oil/gas field has been found, a series of **production wells** is drilled to extract the hydrocarbons. The hydrocarbons are then pumped to oil terminals to be refined, before being sold to provide power or for use in the chemical industry.

During the exploration and production processes, great care must be taken to prevent leaks. While leaks of oil can devastate the environment, gas leaks can cause highly dangerous explosions. If the oil leaking from an oil well catches fire, it can cause enormous environmental problems and is very difficult, dangerous and expensive to put out. This means that there has to be very careful monitoring during borehole drilling, which has to continue right through the production life of a well.

6.3 Mineral prospecting and mining

All the mineral deposits that were easy to find have already been found, so geologists hunting for minerals today have to use a wide range of prospecting techniques in their search for **anomalies**. A mineral anomaly is something that is different from the background data, so if the background copper content of rocks and soils in a region is less than ten parts per million copper, and a soil anomaly of 35 parts per million copper is found, there may be a copper deposit nearby.

Different techniques are used in searching for different minerals, but the principles are similar. First a survey is carried out across a large area. When an anomaly is found, much more detailed surveys are carried out to pinpoint the origin of the anomaly and outline its size and shape. Then a series of trenches or boreholes is used to find the source of the minerals producing the anomaly. At this stage, the prospecting geologist will probably hand over to a mining geologist, who will then excavate pits for evaluating the ore while carrying out a programme of borehole-drilling to outline the three-dimensional size, shape and richness of the ore body. If the deposit is economically viable, and so could give a profit to the mining company, a commercial mine will be excavated to exploit the **ore** (an ore being an economic concentration of metal minerals).

Geologists working for mining companies prospect either greenfield regions, where no ore deposits have previously been found, or brownfield areas, near known deposits, where other similar deposits may be found. If you were prospecting a greenfield area of country with unknown geology, you might first examine any remote sensing data for the region for unusual features, including satellite data using visible light or other parts of the spectrum, and aerial photographs. The next stage might be to fly a geophysical survey, during which variations in gravity and geomagnetism are mapped. This would be followed up by work on the ground, where more detailed geophysical surveys may be carried out. Geomagnetic ground surveys would provide more detail on magnetic anomalies, whilst electrical surveying might find highly conducting (low **resistivity**) ore deposits. Geiger counter surveys would be used to find radioactive uranium-bearing deposits.

Geochemical surveying would be carried out to find, for example, copper, lead, zinc and uranium anomalies but also anomalies of 'pathfinder' elements that are often associated with other ore deposits, such as molybdenum for copper, mercury for lead and zinc,

Figure 6.5: Electrical resistivity surveying.

and arsenic and silver for gold deposits. **Heavy mineral surveys** could find titanium ores, diamonds and gold. Geochemical and heavy mineral surveys begin by sampling the stream sediments of a region and sending the samples to labs for analysis. Any anomalies are followed up, upstream, by more intense stream sampling and later by soil sampling, normally on a grid pattern, to pinpoint the source of the anomaly.

Mineral exploration geologists spend most of their time in the field, often in large and developing countries where the geological potential is least well known. Mining geologists are based in mines, which may often be in remote areas. They explore rock sequences and ore deposits ahead of the miners, using evidence from surface or underground drilling but sometimes with geophysical methods as well. This is important rock detective work, since the work of the miners and the profit of the mining company is based on the decisions of the mining geologist.

Geological work with the mining industry fluctuates with world and local economies, but there will always be need for natural resources and the expertise of mineral exploration and mining geologists (Figure 6.1).

6.4 Hydrogeology

Hydrologists study the whole of the water cycle, both above and below ground, but **hydrogeologists** focus particularly on subsurface water, called **groundwater**. When it rains, water **infiltrates** into the ground and percolates down into the rocks beneath.

Figure 6.6: Groundwater flowing out of the bedrock in a spring.

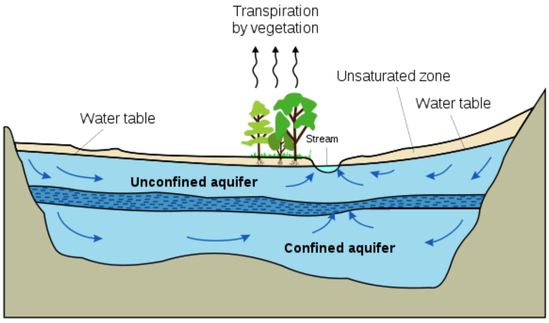


Figure 6.7: Water flows down through the unsaturated zone to the water table and then flows sideways as groundwater, emerging naturally in springs or rivers.

If these rocks are permeable the water will continue to run down until it reaches the **saturated zone**, where all the pore spaces are full of water. The top of this zone is called the **water table** and you can often see the top of the water table by looking down a well. The water table is not flat but is higher under hills and lower beneath valleys, so the groundwater flows slowly downhill, towards the valleys. Where the water table reaches the ground surface, water flows out of the ground, in a **spring**, marsh or bog, or directly into rivers, lakes or the sea.

A permeable rock containing water is called an **aquifer**. If part of the aquifer is beneath an impermeable layer, this is a **confined aquifer** (Figure 6.7). Boreholes drilled into aquifers to extract water are called wells and if wells are drilled into confined aquifers, water may flow naturally out of the well under pressure.

The job of the hydrogeologist is to find aquifers in places where there is not enough surface water from rivers or reservoirs to supply the population. When the hydrogeologist has examined the regional geology and found areas where there are likely to be permeable rocks containing groundwater, an exploratory well is drilled. If the well hits water, the water may naturally flow out of the ground, if the aquifer was confined, but normally, the water will need to be pumped from the well.

When a possible aquifer is found, the hydrogeologist will investigate if the well can produce a reliable water supply by carrying out **pumping tests**. A series of test wells is drilled in a line on either side of the first borehole. Then water is pumped from the central borehole. This causes the water table to be drawn down to form a '**cone of depression**' around the pumping borehole and the shape of the cone of depression can be found by measuring the height of the water in the test wells. If the sides of the cone of depression are steep, the rock is not very permeable, water flows only slowly into the pumping well and will not produce enough reliable water. However, if the cone of depression is broad, water flows easily into the pumping well from the surrounding rock and a reliable water source has been found.

Figure 6.8: A wind pump extracting groundwater to be used by agriculture.

Since many parts of the world will always be short of surface water, the job of the hydrogeologist is vital. In many regions, groundwater is the main source of water for agriculture, industry and the population. A major global problem is that in many of these places the groundwater is being extracted at a greater rate than it is being replaced by rainwater. This water will eventually run out and cannot be replaced. As the world requires more and more water, this will probably become one of the most critical environmental issues on Earth in the future.

Hydrogeologists also play an important part in planning new surface reservoir sites. They examine the reservoir and dam sites to ensure that the rock is not so permeable that water ponded behind the dam will either seep away into the rocks beneath, or flow through the rocks under the dam, and be lost. These studies examine the permeability of the rocks and their direction of dip, since permeable rocks that dip towards the site will tend to bring water into the reservoir, but those that dip away will drain the reservoir water. Where rocks are too permeable then plastic membranes can be laid and rock fractures can be filled, but these measures are very expensive. Hydrologists also work with geotechnical engineers to monitor groundwater flow in the rocks surrounding reservoirs, since if the pore water pressures in unstable rocks become too great during storms, the material can slump into the reservoir causing a disastrous flood. This happened in the 1963 Vajont

Dam disaster in Italy, when the wave of water flooding over the dam killed 2,500 people in the valley below.

Hydrogeologists also monitor groundwater flows and pollution near waste disposal sites, contributing to environmental geological studies. Try modeling groundwater flow and pollution yourself, using the 'From rain to spring: water from the ground' activity at `http://www.earthlearningidea.com`.

6.5 Environmental geology

Environmental geologists have a wide variety of geoscience-related work, ranging from planning for and monitoring modern raw-material extraction and waste disposal sites, to helping to clear up (or **remediate**) old extraction sites and other polluted areas. Environmental geological work overlaps the work of hydrogeologists but is broader, focusing on all the environmental issues concerning a geological site. Environmental geologists manage the environmental concerns of working quarries and mines, advising on where banks and reservoirs should be sited, where landscaping should take place and vegetation planted. Similarly they contribute to the planning of waste disposal sites, monitoring them during their working lives, and ensuring that they are properly remediated and monitored afterwards. Environmental geologists often work with other scientists such as environmental biologists and geographers, ensuring that after sites have closed, they are made suitable for their later use, in agriculture or for public amenity.

A major environmental problem in old mining areas is **acid mine drainage** (Figure 6.9). While the mines were working, water was being pumped out and minerals became exposed to the air and oxidised. When the pumping stopped, the mines filled with water, dissolving the oxidised minerals to make a highly acid solution. When the mine fills up, the water overflows into nearby streams, polluting them and killing all life in the river downstream. This is just one of the many water pollution problems that environmental geologists tackle.

Disused heavy industrial sites, including gasworks, often have badly polluted soils beneath them caused by nasty fluids that leaked from them while they were working, including oil products, solvents, pesticides and heavy metals. Before these industrial brownfield sites can be used for any other purpose such as house-building, the soils have to be remediated. The polluted soils must be extracted, treated and disposed of in new, carefully controlled sites. This too is the work of the environmental geologist, enabling old industrial sites to be reused.

It is not surprising that most environmental geologists today are employed in developed countries where extractive and other industries were not carefully controlled in the past, and where building space is precious and polluted brownfield sites have to be re-used. As other countries develop in the future, they should be able to learn from past mistakes and preserve their own environments more effectively as extraction and industrialisation develop.

Figure 6.9: Acid mine drainage from an abandoned mine in Spain.

6.6 Geotechnical engineering

Geotechnical engineers study building foundations and the earth materials in which other constructions, such as dams, bridges, roads, railways and waterways are sited, as well as landfill and coastal protection sites. The earth materials involved include soil, surface deposits from rivers and glaciation, and the bedrock beneath. A new geotechnical project will begin by researching the information already available from maps and other publications. Geotechnical engineers will assess the likely strength of the earth materials involved, and will be looking out for faults, fractures and other weaknesses in the bedrock. They will also be looking for particular problems such as natural features, like caves and potholes, or features caused by past human activity, such as mining, quarrying, waste disposal or poor foundations of previous constructions. They will research potential problems from natural hazards too, like danger from landslides, or sediments which might 'liquefy' and collapse in earthquakes.

The geotechnical engineer will visit the site, assess any exposures of earth materials and then carry out an investigation, usually involving a pattern of soil samples or boreholes and the testing of the materials found; sometimes geophysical investigations are also used. The next stage is the planning of suitable foundations and other constructions to cope with the findings of the investigation. Then as construction continues, the geotechnical engineer will continue to monitor the site to ensure that everything works as planned.

Building work uses a range of foundation types, from simple foundations for smaller buildings on stable materials to deep foundations for tall buildings, or buildings on less

Figure 6.10: A slab foundation, built to spread the load of a smaller building.

Figure 6.11: Deep foundations being constructed in Spain.

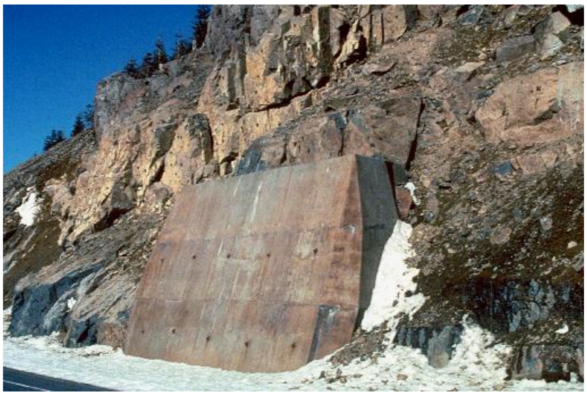


Figure 6.12: A retaining wall supporting weaker materials in a cutting.

Figure 6.13: Stone-filled gabions, stabilising a river bank.

stable material. These may need vertical columns of steel-reinforced concrete called **piles** to be hammered into the ground, or other specialised structures.

Dams need particular sorts of foundations, depending on their design, whilst transport routes need well-constructed embankments, **cuttings** and tunnels, and bridges with well-engineered foundations. Where cuttings and tunnels are excavated into weaker materials, these are dealt with in different ways, from removing material to make more stable shallow slopes, to supporting it with walls or stone-filled **gabion cages**. Similar methods are used to stabilise river banks and coastlines. Meanwhile, rivers prone to flooding have artificial banks called levées or dykes constructed on their banks, built of rock, concrete or gabions.

While building continues across the world, geotechnical engineers will always be in demand.

Figure 6.14: Did an asteroid impact cause dinosaurs to become extinct?....

Figure 6.15: ... or did huge volcanic eruptions cause the dinosaurs to die out?

6.7 Academic research geologists

Academic research geologists are usually based at universities but may also be employed in government agencies such as Geological Surveys. Wherever they operate from, the scientific research process is similar, and is also similar to the investigational work carried out in science courses at schools and colleges. First the geoscientist has to become familiar with the area of study, usually by reading published materials, consulting maps and photographs and conducting fieldwork. The next stage is to develop a research question or questions (a hypothesis or hypotheses) that need to be answered - this will usually involve further reading and data-collection. Then the project swings into action, evidence is collected and recorded in a variety of different ways including: field notes, field diagrams, photographs, measurements, samples and specimens, maps, logs of strata and technological data. Then the geoscientist assembles all the data to provide an answer to the research question posed. Finally the results are written up for publication, but before they can be published, they are '**peer-reviewed**' by other scientists who check that the work done and the report written, are up to the standards expected of scientific publications.

This might sound a simple and straightforward process, but the reality is usually rather different. Often the research question set in the first place turns out not to be quite the right question, and needs modifying. Meanwhile the research usually throws up a whole range of new research questions that need answering. Nowadays research questions are frequently addressed by research teams, involving much discussion, debate and sometimes disagreement during the research. This research work is often at the 'cutting edge' of science, discovering new scientific information that has never been known before. Most researchers work on topics that are vital to human existence, such as 'climate change' whilst a few others work on 'blue skies' research, studying things that have no known value (but which often turn out later to provide new scientific insights).

An example of this is investigations into the extinction of the dinosaurs and other major extinctions of the past. At the moment, there are two main competing theories to account for mass extinctions. Some scientists argue for an 'impact theory', where an asteroid hit the Earth, causing a massive impact, tsunamis, wildfires, and thick clouds of dust that hid the sun, killing the vegetation and most of the animals that lived on the vegetation. Other geoscientists argue that the extinctions are connected with massive outpourings of lava, producing volcanic gases and ash, that transformed the climate of the Earth, affecting all life. Still others argue that the extinctions might have been caused by a combination of events, including these, or that some extinctions had one cause while others had different causes. The only way of deciding which of these ideas is the most likely, is to collect more evidence, similar to that already collected from many parts of the Earth including, geological evidence of lavas and impacts, geophysical evidence of impact craters, geochemical evidence from sediments, fossil evidence of species present before and after extinctions, and detailed logging of geological sequences at the times of the Earth's major extinction events. What will the answer(s) be? If you become a geologist, you might help to find out.

Some people might complain that it is not worth researching major extinctions in the distant geological past, but whatever we find out about ancient extinctions, might help us to understand how species become extinct today, together with the impacts that climate change might have on future extinctions. So geologists contribute not only to debates about the past, but also to discussions on what is happening on our planet today, and what might happen in the future.

The world of academic research is changing because most of the funding for research comes from large national organisations such as government councils or charities. Research scientists have to put in bids for funds to run their research programmes, these are 'peer reviewed' and the successful bids get funding. Most successful bids are submitted by research groups of several scientists and much of the actual work is done by research students. Even though quite a lot of the work involves high technology, using expensive machines and computers, geoscience information still needs to be collected from the ground, with fieldwork and field data collection being key parts of the job. The result of all this is that few research scientists now work alone and good team work is vital (Figure 6.16). It is also vital that research scientists communicate their work to their colleagues and to the public, showing that today's research scientists need to play a wide range of different roles if they are to be successful.

Since university geologists not only carry out research, but also teach on university courses, new students learn how to become future geologists and also how to become research scientists. With the past, present and future to investigate, research geoscientists will always play a crucial role in studying and contributing to how our planet evolves in the future.

Studying geoscience can offer a wealth of opportunities, both in the commercial and research fields. It also provides a sound foundation for people to move into lots of different jobs, with geologists playing important roles in government, law, education, media and a wide range of commercial positions. A number of websites contain more details of

Figure 6.16: A team of geologists measuring the magnetic field on the flanks of the Mt St. Helens volcano.

geoscience opportunities and the career paths of different geoscientists from a wide range of backgrounds. Geoscientists clearly play a vital role on our planet today and their investigations are critical to the future of the Earth.

Glossary

Absolute age The age of a rock or an event in years, or millions of years

Acid mine drainage When mines are working, the water table is often lowered, allowing minerals to oxidise; when the mine is abandoned, the water rises and dissolves the minerals, producing acid, which drains from old mine passages into surrounding streams

Acid rain Rain polluted by human-produced chemicals in the atmosphere, such as nitrogen and sulfur compounds, in addition to the normal carbon dioxide content of the rain

Acid test One drop of dilute hydrochloric acid (wear eye protection) is added to the specimen; if it reacts (fizzes), carbonate is present, usually calcium carbonate; used to identify calcite, aragonite, limestone and marble

Aggregate Crushed rock (e.g. limestone, sandstone, granite, basalt) or sand and gravel; used to add to concrete, for foundations and for railways

Andesite A fine-grained chemically intermediate igneous rock found in lavas and small intrusions; usually grey in colour

Angular unconformity Unconformity, where the rocks beneath the unconformity surface dip at a different (usually steeper) angle than the rocks above

Anomaly A feature (e.g. high copper concentration; high magnetic field strength) that differs from the background

Anticline Upfolded rocks (strictly, folded rocks with the oldest rock in the centre of the fold - since, if the sequence was tectonically inverted, anticlines would be downfolds)

Aquifer A permeable rock layer containing water

Aragonite A mineral ($CaCO_3$); an allotrope of calcite (same chemical make-up, different atomic structure)

Archaea Simple organisms that have cells with no nuclei

Asteroids Small bodies in outer space that sometimes collide with planets

Asthenosphere The zone in the mantle beneath the lithosphere, between around 100 and 250 km beneath the Earth's surface; is partially molten (1 - 5% liquid) and flows, carrying the tectonic plates

Attrition The rounding of rock fragments during transportation

Aureole (metamorphic) The zone of baked rock around an intrusion; the thermal metamorphic zone

Axial plane surface A plane formed by joining the axes of folded layers together

Baked margin The thin zone of metamorphosed rock along the margin of a narrow igneous intrusion, such as a dyke or sill; a thermal metamorphic zone

Basalt A fine-grained mafic (magnesium and iron-rich) rock, dark in colour; commonly forms lavas and small intrusions

Bed (sedimentary) A layer in a sedimentary rock, originally laid down as a layer of sediment

Benioff zone Zone of earthquakes sloping diagonally downwards where a plate is subducting (sometimes at 90°)

Biofuel Crop grown to produce power for human use

Biological weathering The physical and chemical effects of plants on rocks and soils, including the extensive effects of microscopic bacteria

Borehole core A cylinder of rock drilled from a rock formation using a hollow drill bit

Breccia A coarse-grained rock with angular grains (sedimentary or formed along a fault as a fault breccia)

Brittle behaviour When a material behaves in a brittle manner, it breaks (fractures) under pressure

Bund An embankment; bunds are often built around quarries to reduce their environmental impact

Calcite A mineral ($CaCO_3$), usually white or colourless, can form good 'dog tooth'-shaped crystals, good cleavage, fairly low hardness, reacts with dilute acid, is the main mineral in limestone and marble, is found as a gangue mineral in veins and as cement in some sedimentary rocks

Cap rock An impermeable rock that can trap fluids (oil, natural gas, water) underground; includes impermeable mudstone, shale, clay, salt or clay layers along some faults

Carbon capture The reduction of carbon emissions by collecting the carbon dioxide released by coal-, oil- and gas-burning power stations and storing it in abandoned oil or gas fields - still experimental; also called carbon sequestration

Carbon footprint Relates to the amount of carbon dioxide released to the atmosphere by the activities of an individual or organisation; usually related directly to the energy used

Carbon sequestration The reduction of carbon emissions by collecting the carbon dioxide released by coal-, oil- and gas-burning power stations and storing it in abandoned oil or gas fields - still experimental; also called carbon capture

Carbon trading A commercial system designed to offset carbon production by one activity (such producing power from fossil fuel) with another that reduces carbon production (such as planting trees); 'units' of carbon may be 'traded' by different organisations

Cement Formed of minerals that crystallise in the pore spaces of sediments, hardening them into sedimentary rocks; usually quartz or calcite

Cephalopod Cephalopods alive today include octopus and squid, but the geologically important ones lived in coiled shells and are nearly all extinct; the most well known shelled cephalopods are the extinct ammonites and the living *Nautilus*

Chemical weathering The chemical breakdown of rock surfaces; rainwater and soil-water play critical roles

Chilled margin The edge of an igneous intrusion, that has cooled more quickly than the inside, and so is formed of finer-grained rock

Clay minerals Fine-grained sedimentary minerals; formed from the chemical breakdown of silicate minerals like feldspar and mica

Clean coal technology The use of new technology to burn coal and produce power, whilst keeping the release of polluting and greenhouse gases to a minimum

Cleavage (mineral) The way in which a mineral breaks, parallel to the weaknesses in its atomic structure; minerals can have no cleavage, or one, two, three, or four directions of cleavage

Cleavage (slaty or metamorphic) The slaty foliation of low-grade regional metamorphic rocks; forms slates

Coarse-grained igneous rock Rock formed by slow cooling of a magma, deep underground; crystals easily visible

Columnar basalt Basalts that have contracted as they cooled to form polygonal columns; the columns are usually vertical

“Concentrate and contain” landfill method The landfill method of disposing of waste in impermeable sites that are capped, with no leakage to the surrounding environment, as used in recent years

“Cone of depression” The inverted cone-shape of the water table around a pumping water well

Confined aquifer A water-bearing rock (aquifer) beneath an impermeable layer; the water is usually under pressure and can flow naturally through boreholes to the surface

Conglomerate A sedimentary rock formed of rounded pebbles (at least 2mm in diameter), usually with a fine-grained matrix

Conservative margin The sliding margin of a tectonic plate, where material is neither constructed or destroyed, but is conserved; also called a transform fault

Constructive margin The margin of a tectonic plate where new plate material is formed as plates are moved apart; also called a divergent plate margin

Continental Drift (Theory of) Alfred Wegener’s theory of the early 1900s, that the continents had moved across the Earth’s surface; the theory was later modified and included in the Theory of Plate Tectonics

Convection current Flow caused when heated material rises, because of its lower density, then cools and sinks, producing a continuous current

Convergent margin The margin of a tectonic plate where plate material is ‘destroyed’ as plates converge, either by partially melting and rising as magma, or by being absorbed in the mantle; also called a destructive margin

Core (borehole) A cylinder of rock drilled from a rock formation using a hollow drill bit

Correlation The use of fossils to identify rocks of the same age

Cross bed A bed laid down at an angle to the horizontal, usually in underwater dunes or wind-formed sand dunes

Cross-cutting relationships (law of) The stratigraphic law that anything (faults, joints, dykes, plutons, unconformity surfaces, etc.) which cut across anything else is younger

Crust The outer part of the Earth above the mantle, differing chemically from the mantle; it comprises oceanic crust under oceans (5 - 10 km thick) (30 - 50 km thick) and continental crust beneath continents and averages 15 km in thickness

Crustal extension The results of tensional stress; the rocks take up more space on the surface than they did before deformation

Crustal shortening This results of folding and/or faulting under compressional forces; as a result, the surface rocks occupy less space

Cuesta An asymmetrical ridge in the landscape that typically forms where a tough rock with a shallow dip (of usually less than 10°) overlies a weaker rock; also called an escarpment

Current ripple marks Non-symmetrical ripple marks formed by flowing water or wind; the steeper slope is in the down-current direction

Cuttings Wide, deep trenches excavated through hills or ridges for transportation routes

Debris flow The downhill flow of debris from a landslide; debris flows contain coarser material than mudflows

Deep focus earthquake An earthquake that originates between 300 and 700 km below the surface; these occur only at destructive convergent plate margins, where plates are subducted

Deep mine (mine) An underground excavation, usually for metal ores, other minerals or coal; mine excavations usually have vertical shafts and horizontal adits

Deep time Geological time

Desiccation cracks Polygonal cracks left by drying mud - can be preserved in mudstones; also called mudcracks

Destructive margin The margin of a tectonic plate where plate material is 'destroyed' as plates converge, either by partially melting and rising as magma or by being absorbed in the mantle; also called a convergent margin

Diagenesis The change of sediments to sedimentary rocks, through compression of the overlying sediments and cementation (cement being deposited in pore spaces); also called lithification

Diamond A mineral formed of carbon (C), usually colourless, forms good crystals, extremely hard, rare

"Dilute and disperse" landfill method The old landfill disposal method of allowing rainwater to disperse toxic elements of landfill in the rocks beneath

Dinosaur A type of reptile, now extinct

Dip The amount of downward slope of rock layers or structures, measured from the horizontal

Discordant (drainage) A river system cutting across underlying geology and not affected by it; often caused by a system that developed on overlying rocks, which have since been cut through and eroded away

Divergent margin The margin of a tectonic plate where new plate material is formed as plates are moved apart; also called a constructive plate margin

Dolerite A medium-grained mafic rock, dark in colour; commonly forms dykes and sills

Downhole logging Measurements made remotely by lowering sensors down a previously-drilled borehole

Ductile behaviour When a material behaves in a ductile way, it bends and flows under pressure, and stays in the same shape when the pressure is removed

Dune A mound of sand formed under water or by the action of wind; contains cross bedding

Dyke An igneous intrusion that cuts across the bedding planes of sedimentary rock or across igneous or metamorphic rock

Earth System Science The study of the Earth as a series of systems that interact with one another

Earthquake (deep focus) An earthquake that originates between 300 and 700 km below the surface; these occur only at destructive convergent plate margins, where plates are subducted

Earthquake (intermediate depth) An earthquake that originates between 70 and 300 km below the surface; these occur only at destructive convergent plate margins, where plates are subducted

Earthquake (shallow focus) An earthquake that originates between 0 and 70 km below the surface; these occur at all plate margins but shallow focus earthquakes alone occur at constructive (divergent) and conservative (transform) plate margins

Earthquake focus The place under the surface where the fracture of a fault produces earthquake shock waves

Ecological niche The local environment in which an organism lives and interacts with other organisms

Elastic behaviour When a material behaves elastically, it deforms under pressure, but then bounces back to its original shape when the pressure is removed

Epicentre The point where the shock waves from an earthquake first reach the Earth's surface - the surface waves then radiate out from this point like ripples on a pond; most earthquake damage usually occurs at the epicentre

Erosion The removal of solid material, which has often been loosened by weathering - by gravity, flowing water, wind or ice; erosion is usually the beginning of transportation

Eukaryotes Organisms that have cells with nuclei

Evaporite deposits (or evaporites) Salts (e.g. halite) that crystallise out when a lake or arm of the sea evaporates

Exceptional preservation (lagerstätten) Unusual examples in the fossil record where groups of fossils are very well preserved, usually with many of their soft parts attached

Exfoliation The formation of curved sheets of rock by weathering of the rock's surface; common on granites affected by heating and cooling weathering

Exploration well A borehole drilled to prospect for oil or gas (or water)

Extinction The dying out of a group of organisms

Extrusive (lava, pyroclastics or igneous rock) Extrusion is caused by magma reaching the surface and erupting volcanically as lava, ash, or larger pyroclastic materials

Facing stones Thin slabs of ornamental rock attached to the walls of buildings

Fault The brittle failure of rock under pressure, with movement of one side relative to the other; earthquakes are caused by faulting

Fault breccia Fractured angular rock fragments in a fault plane, caused by rock breakage during fault movement

Fault displacement The amount of movement of layers by faulting, measured along the fault plane

Fault plane The fracture surface of a fault, along which relative movement occurred

Fault scarp A steep slope in the landscape caused when rocks either side of a major fault have differed in their resistance to erosion

Faunal succession (law of) The law that all animals follow one another in geological time in a predictable sequence; plants have a similar predictable sequence - we now know that this is due to evolution

Feedback Change in a system resulting in further change, either reinforcing the change (positive feedback) or resisting the change (negative feedback)

Feldspar A mineral silicate, usually white, sometimes pink, can form good almost rectangular crystals, good cleavage, hard, common in igneous and some metamorphic rocks

Fine-grained igneous rock Rock formed by quick cooling of a magma, e.g. in a surface lava; crystals usually too small to see, even with a hand lens

Focus (earthquake) The place under the surface where the fracture of a fault produces earthquake shock waves

Fold The ductile bending and flow of rock under pressure resulting in bent layers; folds can be gentle and open, or tight

Fold axis The place where a rock is most bent by folding

Fold limb The sloping layers either side of a fold axis

Foliation The 'layered' texture of regionally metamorphosed rocks, caused by the metamorphic minerals being aligned with one another; includes metamorphic cleavage in slates, foliation in schists, and banding in gneisses

Foreshock A minor earthquake that takes place before a more major earthquake

Fossil Traces of an organism preserved in rock (usually regarded as more than 10,000 years old)

Freeze-thaw weathering Weathering caused by many cycles of freezing and thawing

Gabbro A coarse-grained mafic (magnesium/iron-rich) rock, with predominantly dark minerals

Gabions (gabion baskets) Galvanised wire mesh cubic or rectangular containers around a metre or so across filled with pebbles or larger rock; used to stabilise slopes such as cuttings, river banks and coastal cliffs

Gaia Hypothesis The idea that life on Earth causes negative feedback which regulates many of the Earth's systems; proposed by James Lovelock

Galena A lead-containing mineral (PbS), silvery grey, metallic lustre, cube-shaped crystals, good cleavage, feels very dense, grey streak, low hardness (soft), found mainly in mineral veins

Gangue mineral Uneconomic mineral, like quartz and calcite, that may be thrown away when metal ores are mined

Garnet A silicate mineral, usually red or pink, often forms ball-shaped crystals, no cleavage, hard, found mainly in medium and high grade metamorphic rocks

Geochemical survey Using chemical methods to explore and understand the Earth; the chemical testing is usually done in laboratories nowadays, using high tech methods

Geohazard A geological process that causes risk to humans and human constructions

Geological time The time from the origin of the Earth (around 4,560 million years ago) to the present day

Geopark An area of international importance for its geological interest, designated by UNESCO (the United National Educational, Scientific and Cultural Organisation)

Geophysical survey Using the methods of physics to probe the Earth including: seismology, gravity, electrical methods, magnetic methods and radioactivity

Geotechnical engineering The study of building foundations and the soil/bedrock in which constructions, such as dams, bridges, roads, railways and waterways are sited, together with landfill and coastal protection sites

Geotextiles (geofabrics) Tough textiles used to cover steep slopes to reduce erosion

Glacial period (glaciation) A time when there were extensive ice sheets on Earth

Glacial till Sedimentary deposit formed largely of mixed mud and boulders, deposited by melting ice

Gneiss A metamorphic rock formed by high-grade regional metamorphism; contains metamorphic banding, which sometimes has complex folding

Gold (native gold) A mineral made of one element (Au) that can be found in mineral veins or eroded from veins and deposited in sediments

Gondwana A 'supercontinent' of all the current southern hemisphere continents (and India) formed around 550 million years ago

Graded bed A layer of sediment that is coarser at the bottom and becomes finer upwards; frequently deposited by turbidity currents

Granite A coarse-grained, pale-coloured, silica-rich igneous rock

Graptolite Extinct animals that formed small colonies strung together in saw-blade-like shapes; lived in the open ocean

Greenhouse effect The sun's radiation absorbed by the Earth's surface is re-radiated as infra-red radiation (heat) that is absorbed by 'greenhouse gases' such as carbon dioxide and methane, causing the surface of the planet to be warmer than it otherwise would be; the gases behave rather like the panes of glass in a greenhouse 'trapping' the heat

Greenhouse gas A gas in the atmosphere that absorbs infra-red radiation (heat); includes carbon dioxide, methane and water vapour

Halite A mineral, NaCl, white or pink, cube-shaped crystals, good cleavage, low hardness (very soft), soluble in water, forms rock salt deposits

Hard parts The solid parts of organisms, such as shells, bones, teeth or cartilage, which are most likely to become fossilised

Hardness (mineral) Usually measured by the scratch test, harder minerals will scratch softer ones; Mohs' scale of hardness ranges from 1 (very soft talc) to ten (very hard diamond)

Heat engine A pump and heat exchangers used to extract heat from the ground or the air to heat buildings; can be reversed to add heat to the surroundings in order to cool buildings

Heating of hydrocarbon source rocks Rocks have to be heated to release hydrocarbons; most gas and oil are released between 100 and 200°C; above 200°C they are destroyed

Heavy mineral survey Stream or soil survey for minerals of higher density than average, such as diamond, gold or ilmenite (titanium ore)

Hematite An iron-containing mineral (Fe_2O_3), earthy red, metallic lustre, feels dense, red streak, usually hard, often found in irregular masses

Hominid The family (group) of primate species, of which *Homo sapiens* is the only one living; all the other hominid species have become extinct

Hydrocarbon The fossil fuels, coal, crude oil, and natural gas

Hydrocarbon reservoir rock Rock with enough pore space and permeability to hold hydrocarbons and to allow them to flow out

Hydrocarbon source rock Rock from which crude oil or natural gas originally came; the decay of plankton in mudstones/shales produced oil and some gas whilst most gas comes from coal

Hydrocarbon trap The shape of a formation that can trap hydrocarbons underground; includes anticlinal, fault and unconformity traps and traps associated with salt domes

Hydrogeology Study of subsurface water, called groundwater

Hydrology Study of the whole of the water cycle, both above and below ground

Hydrothermal fluid Hot watery liquid produced by some magmas and by the heating of rocks deep underground; rises and cools to crystallise minerals

Igneous rock Rock formed by the cooling of liquid magma or lava

Impermeable A material that fluids cannot flow through

Included fragments (law of) The stratigraphic law that anything (e.g. pebbles in conglomerates, fragments of the surrounding rock in plutons) included in anything else must be older

Infiltration (of water) Water percolating down into the ground surface, usually from surface precipitation (rain, snow, etc.)

"Integrated waste management" The modern landfill method involving the "reduce, reuse, recycle" approach; remaining waste is disposed of using "concentrate and contain" methods

Intermediate An igneous melt or rock rich in neither magnesium/iron nor silicon; these elements have roughly equal ratios

Intermediate depth earthquake An earthquake that originates between 70 and 300 km below the surface; these occur only at destructive convergent plate margins, where plates are subducted

Intrusion Magma that has penetrated rocks underground and has solidified there

Intrusive (magma or igneous rock) Intrusion is the penetration of magma into rocks underground, which subsequently solidifies

Joint A fracture which is usually straight, where the rock on either side has not moved relative to the other (and so is not a fault); often found as groups of parallel joints together, in joint sets

Keeling Curve The graph showing the increase of carbon dioxide in the atmosphere since 1958, first measured by Charles Keeling

Lagerstätten (exceptional preservation) Unusual examples in the fossil record where groups of fossils are very well preserved, usually with many of their soft parts attached; from German meaning 'place of storage'

Lahar A 'mudflow' of volcanic material, predominantly ash with blocks; lahars flow like liquid concrete at tens of kilometres per hour (even though they are flows of pyroclastic materials, the term 'pyroclastic flow' has a different meaning)

Lamination Thin layer of mud; can be formed into laminated mudstone or shale

Landfill Material such as domestic refuse (trash or garbage) or other waste buried in disused quarries, pits or other depressions in the landscape

Landfill membrane The impermeable plastic liner used to line permeable landfill sites

Landslide (or landslip) The downslope movement of geological materials; landslides can be slow or catastrophically quick, and include rock fall, slips, slides and flows of material

Landslip (or landslide) The downslope movement of geological materials; landslips can be slow or catastrophically quick, and include rock fall, slips, slides and flows of material

Lateral continuity (principle of) The stratigraphic principle that strata were originally deposited in laterally continuous sheets over large areas

Lava Liquid rock at the surface

Leachate The poisonous liquid produced by decaying waste

Limb (fold) The sloping layers either side of a fold axis

Limestone A sedimentary rock made largely of calcium carbonate ($CaCO_3$); formed mainly in tropical and sub-tropical seas from fossil debris or the evaporation of sea water

Liquefaction (of loose material) When loose surface material is shaken by an earthquake, it can lose its internal strength and ‘liquefy’, causing buildings to sink and collapse

Lithosphere Outer rigid shell of the Earth, around 100 km thick, comprising the crust and part of the upper mantle; broken into the tectonic plates

Lustre (mineral) The surface appearance of a mineral, for example dull, glassy or adamantine (diamond-like)

Ma Millions of years (mega annum)

Mafic An igneous melt or rock rich in magnesium (ma) and iron (fic)

Magma Liquid rock underground

Magnetic field (of the Earth) The Earth’s magnetic field that, at different times in the past has ‘flipped’ so that the current north magnetic pole has become the south pole, and *vise versa*

Magnetic stripes The linear ocean floor magnetic anomalies detected by magnetometer surveys that show ‘normal’ and ‘reversed’ mirror-image patterns on either side of oceanic ridges

Mantle The zone of the Earth beneath the crust (around 15 km mean depth) to the core (around 2900 km depth); solid apart from the narrow zone of the asthenosphere, which is 1 - 5% liquid

Marble Metamorphic rock formed of calcite ($CaCO_3$), formed by the metamorphism of limestone

Mass extinction A point in geological time when significant numbers of groups of organisms died out, all at a similar time

Massive Description of a rock in a rock face which has no obvious layering

Metal ore Metal-containing minerals that are rich enough to mine

Metamorphic rock Rock formed when another rock has been recrystallised by increased heat and/or pressure (without fully melting)

Metamorphism The recrystallisation of a rock under increased heat and/or pressure (without fully melting)

Metaquartzite (quartzite) Metamorphic rock formed largely of quartz, formed by the metamorphism of pure quartz sandstones (also called quartzite)

Mica A mineral silicate, usually colourless or black, forms platy crystals, good cleavage in one direction, low hardness (soft), common in many igneous and some metamorphic rocks

Mine (deep mine) An underground excavation, usually for metal ores, other minerals or coal; mine excavations usually have vertical shafts and horizontal adits (an opencast coal pit is called an opencast mine)

Mineral A naturally occurring inorganic compound or element (or, more precisely, a naturally occurring inorganic compound with a definite chemical composition, a definite atomic structure, and physical properties which vary between known limits)

Mountain-building episode Rock deformation and metamorphism caused by a plate collision that formed mountain ranges

Mudcracks Polygonal cracks left by drying mud - can be preserved in mudstones; also called desiccation cracks

Mudflow The downhill flow of mud, usually from a landslide; usually finer-grained than debris flows

Mudstone A sedimentary rock formed of mud-grade sediment

Natural selection Darwin's idea that the best adapted organisms survive in an environment and that the others die and so are unable to reproduce

Negative feedback Change in a system, where the effects reduce the change

Normal fault Tensional fault where the rocks on one side have slid down relative to the rocks on the other, usually along a steep fault plane of 60°or more

"Normal" magnetism When the remnant magnetisation of rock, such as found in the magnetic stripes on the ocean floors, is in the same direction as the Earth's magnetic field today

Nuée ardente (pyroclastic flow) A density flow of red hot ash that flows downhill from a volcanic blast at speeds of up to hundreds of kilometres per hour (does not include lahars); from the French 'glowing cloud'

Oceanic ridge The ridges of mountains in oceans where new plate material forms, with a rift valley down the centre; when in the centres of oceans, they are called mid-oceanic ridges

Oolites Tiny balls of limestone (aragonite, $CaCO_3$) formed by waves and currents in strongly evaporating seas

Oolitic limestone A sedimentary rock made of oolites, tiny balls of calcium carbonate that first formed as aragonite and usually later changed to calcite ($CaCO_3$)

Ore An economic concentration of metal minerals

Ore mineral A metal-containing mineral that is rich enough to mine

Original horizontality (principle of) The stratigraphic principle that strata were originally deposited as near-horizontal layers

Pangaea A 'supercontinent' of all the continents on Earth (including Gondwana) that existed between about 300 and 250 million years ago

Partial melting When a substance is heated so that only the low melting point components melt, it is described as a 'partial melt'; in rocks, silicon-rich minerals melt before iron- and magnesium-rich minerals

"Peer review" The checking of scientific publications by other scientists of equal standing - their peers'

Percolation (of water) Water flowing through pore spaces in the ground/soil/rock

Peridotite A coarse-grained ultramafic rock (very rich in magnesium/iron) found in the Earth's mantle

Permeability How quickly a fluid can flow through a rock; given as a flow rate per surface area of rock

Physical weathering The break up of rock surfaces by physical weathering processes, such as freeze-thaw and heating and cooling

Piles Vertical columns of steel-reinforced concrete hammered into weak ground to support foundations

Pillow basalt Basalt that has erupted under water to form pillow-like shapes

Plate (tectonic) The slabs of rigid, solid rock made of lithosphere (comprising the crust and part of the upper mantle) that are moved across the surface of the Earth by plate tectonic movement

Plate Tectonics (Theory of) J. (John) Tuzo Wilson's theory of the late 1960s linking together earlier ideas into a global theory of tectonic plate movement

Plateau A horizontal flat upland area, typical of regions where tough rocks are horizontal

Pluton A large igneous intrusion, often inverted drop-shaped; may be several kilometres across

Pore spaces (or pores) Gaps between the grains; fluids such as oil, natural gas or water can flow through pores, or they may become filled with cement as a porous rock hardens

Pore water pressure The pressure of water in the pore spaces of rocks; high pore water pressure contributes to landslides

Porosity The amount of pore space in a rock; given as a percentage

Positive feedback Change in a system, where the effects increase the change

Primate An order (group) of mammals that includes lemurs, monkeys, apes and humans

Production well A borehole drilled to extract the oil and gas (or sometimes, water) found by previous exploration wells

Pumping tests Tests carried out by drilling a line of boreholes, pumping water from the central one and monitoring the height of the water table in the others, to establish whether or not a water well is viable

Pyroclastic Material ejected by explosive eruptions, including fine-grained ash and volcanic blocks; from the Greek, (*pyro* = fire-formed; *clastic* = broken material)

Pyroclastic flow (nuée ardente) A density flow of red hot ash that flows downhill from a volcanic blast at speeds of up to hundreds of kilometres per hour (does not include lahars)

Quarry A pit or hillside excavated for its raw materials (large pits dug for coal are usually called opencast mines; pits dug for sand or clay may be called sand- or clay-pits)

Quartz A mineral, silicon dioxide (SiO_2), usually grey, white or colourless, hard with no cleavage and a glassy lustre - found in a variety of rocks as well as in mineral veins

Quartzite (metaquartzite) Metamorphic rock formed largely of quartz, formed by the metamorphism of pure quartz sandstones (also called metaquartzite)

Radiometric dating Method of calculating the age (in years/millions of years) of a rock (subject to a measurable margin of error) from the decay of the radioactive elements it contains

Raised beach A narrow flat coastal area, often backed by a cliff, that was formed when sea level was higher, relative to the land; linked to changes in sea level during and after ice ages

Regional metamorphism Rock recrystallisation caused by heat and increased pressure during the mountain-building episodes caused by plate tectonics; affects large areas

Regionally Important Geological and Geomorphological Sites (RIGS) Sites in the UK listed for their geological importance

Relative age Sequenced events, from the oldest to the youngest

Remediation (site) The cleaning up of formerly polluted sites

Reserves The amount of a natural resource available for extraction

Reservoir rock (hydrocarbon) Rock with enough pore space and permeability to hold hydrocarbons and to allow them to flow out

Resistivity (electrical) A geophysical method measuring the conductivity of rock; rocks with high conductivity (low resistivity) may contain metal ores or water

Reverse fault Compressional fault that usually dips at around 45°(between 30 and 60°)

"Reversed" magnetism When the remnant magnetisation of rock, such as found in the magnetic stripes on the ocean floors, is in the opposite direction to that of the Earth today

Ridge Caused by tough rocks that normally dip at more than 10°, with steep slopes on either side

Rift valley The valley formed when the Earth's crust is in tension, as at constructive plate margins; as the rock is pulled apart, the central block slides down along normal faults, creating a long valley

Ripple marks (asymmetrical) Non-symmetrical ripple marks formed by flowing water or wind; the steeper slope is in the down-current direction

Ripple marks (symmetrical) Ripple marks with equal slopes, formed by oscillating waves in shallow water

Rock A naturally-occurring material composed of a mixture of minerals, fragments of rock, and/or fossils

Rock bolt Large bolts used to tie potentially hazardous loose rock sheets and fragments to a rock face

Rock cycle Cycle of weathering and erosion, transportation, deposition, sedimentary rock formation, metamorphism and igneous processes through which all rocks are formed

Rock texture The ways in which the grains of the rock fit together; linked to the shapes, sizes and orientations of the grains

Rodinia An early 'supercontinent' of all the early landmasses about 1000 million years ago

Rounding The removal of sharp corners of angular grains and the smoothing of the surface during sediment transportation; caused by attrition

Saltation Sediment movement by fluid (water or wind) where the grains bounce along the bed

Sandstone A sedimentary rock of sand-grade sediment

Saturated zone The zone beneath the ground surface where all the pore spaces are full of water; the top surface of the saturated zone is the water table

Scarp and vale topography A series of cuestas formed in areas of alternating tough and weak rocks of shallow dip (of usually less than 10°)

Schist A metamorphic rock formed by medium-grade regional metamorphism; contains a coarse mineral foliation with garnet crystals sometimes visible

Scree A slope of angular rock fragments accumulated beneath a rock face

Sea Floor Spreading (Theory of) Harry Hess' theory of the 1960s that the oceans were young and that new ocean material was formed at oceanic ridges as the ocean floor was moved apart

Sedimentary rock Rock made of sediments which are fragments of other rocks (mineral or rock fragments) or fossils; sometimes also laid down by the evaporation of water

Seismic gap The 'locked' part of a fault where no slippage has occurred recently; this is the most likely site of a future earthquake

Seismic survey Method using shock waves to show the positions and shapes of the rock layers beneath the surface

Shale A weak laminated sedimentary rock of mud-grade sediment, that tends to fall apart in your hand

Shallow focus earthquake An earthquake that originates between 0 and 70 km below the surface; these occur at all plate margins but shallow focus earthquakes alone occur at constructive (divergent) and conservative (transform) plate margins

Shotcrete A blanket of concrete used to cover and stabilize an unstable rock face

Silicic An igneous melt or rock rich in silica (silicon dioxide, SiO_2)

Sill An igneous intrusion that follows the bedding planes of rock, and so is parallel to them; can be horizontal, tilted or even vertical, paralleling the bedding

Site of Special Scientific Interest (SSSI) A site in the UK protected by law for its biological or geological importance

Slate A metamorphic rock formed by low-grade regional metamorphism; contains slaty foliation or cleavage

"Slushball Earth" The theory that the Earth was once nearly covered by ice, but there was probably some areas of non-frozen ocean near the Equator

Smelting The process of separating metal from the impurities in metal ore by heating

"Snowball Earth" The theory that the Earth was once completely covered by ice

Soft bodies Organisms with no hard parts such as shells or bones, which therefore are unlikely to become fossilised

Solution (transport by) Dissolved material carried by water currents

Sorting The sorting out of sediment grains into different sizes during transportation; well-sorted sediments have grains of just one size, e.g. well-sorted sand

Source rock (hydrocarbon) The rock from which oil or natural gas originally came; the decay of plankton in mudstones/shales produced oil and some gas whilst most gas comes from coal

Spring Natural flow of groundwater out of the ground

Stipe A single arm of a saw-blade-like graptolite colony

Strata Sedimentary or volcanic layers, deposited at the Earth's surface

Stratigraphic principles The principles used to understand how layers (strata) were deposited in the past and the sequence of events involved in their deposition and later history

Streak (mineral) Colour left as a scratch on a white tile (or by filing onto white paper)

Strike The two directions at right angles to the dip direction of sloping rock layers; for example, rocks that dip east have a north-south strike

Strike-slip fault The results of shear stresses; when seen from above, one side has moved relative to the other along a fault plane that is usually vertical

Stromatolites Mats of simple organisms (cells with no nuclei) that can form pillars of mats

Structure (sedimentary) The sedimentary features of a sediment or sedimentary rock that are larger than grain size, including features like bedding and cross bedding

Subduction The sinking of an oceanic plate into the mantle at a destructive/convergent plate margin

Supercontinent A large continent formed when plate tectonics brought several continental masses together in the past

Superposition of strata (principle of) The stratigraphic principle that strata deposited on top of other strata are younger

Suspension Sediment movement by fluid (water or wind) where the grains remain buoyed up in the current as they are carried along

Suture line (cephalopod) The junction between the wall of the chamber and the outer wall of the shell; early cephalopods had simple straight suture lines, later ones were much more complex

Syncline Downfolded rocks (strictly, folded rocks with the youngest rock in the centre of the fold - since, if the sequence was tectonically inverted, synclines would be upfolds)

Tectonic Deformation of the Earth's outer layers

Texture (rock) The ways in which the grains of the rock fit together; linked to the shapes, sizes and orientations of the grains

Theca (plural thecae) The living chamber of a single graptolite animal

Thermal metamorphism Rock recrystallisation caused by the baking of surrounding rocks by cooling igneous intrusions; caused primarily by high temperatures

Thrust fault Compressional fault with a sliding surface that has low angle of slope of less than 45°(often around 10°or less); sometimes bodies of rock can be moved tens of kilometres along thrust faults

Till (glacial) Sedimentary deposit largely of mixed mud and boulders deposited by melting ice

Tor Exposed rounded mass of jointed rock in an upland area, typical of granite and coarse sandstone bedrock

Traction Sediment movement by fluid (water or wind) where the grains slide or roll along the bed

Transform fault A major fault offsetting oceanic ridges; the conservative plate margins of plate tectonics

Trap (hydrocarbon) The shape of a formation that can trap hydrocarbons underground; includes anticlinal, fault and unconformity traps and traps associated with salt domes

Trench (oceanic) The deep clefts on the margins of many oceans, where plates are subducted into the mantle beneath

Tsunami Water waves produced by earthquakes or landslips - large tsunamis can be very damaging; the older term of 'tidal wave' is falling out of use

Turbidite A flat sheet of sediment deposited by a turbidity current, often as a graded bed

Turbidity current A billowing cloud of muddy sediment that flows downslope underwater

Ultramafic An igneous melt or rock very rich in magnesium (ma) and iron (fic)

Unconformity A surface between two rock sequences; the first was deposited, formed into rock, probably folded/tilted, and then uplifted and eroded, then the second rock sequence was deposited on the eroded unconformity surface

Uniformitarianism (principle of) Ancient rocks were formed by processes still active on Earth today; 'the present is the key to the past'

Vesicles Gas bubbles preserved as holes (usually spherical), when a lava flow became solid

Volcanic ash Fine-grained solid volcanic material ejected during an eruption, often high into the atmosphere

Volcanic block Coarse-grained solid volcanic material such as boulders ejected during an eruption

Water table The top of the saturated zone under the ground surface; can be seen by looking down a well

Wave ripple marks Ripple marks with equal slopes, formed by oscillating waves in shallow water

Weathering The natural break up and break down of rock and other materials at the Earth's surface, without the removal of solid material

Well A borehole drilled for oil/gas or water; wider wells are excavated for water

Wind turbine Windmill used to produce power

Wind farm A cluster of wind turbines

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Figure 1.14b Diamond in a ring.

Figure 1.14c Garnets in schist.

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Figure 1.15d Mica.

Figure 1.15e Quartz.

Figure 1.18 Breccia.

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Figure 1.23 Dried lake bed, Death Valley, California, USA.

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Figure 1.35 Fossil coral.

Figure 1.47 Volcanic ash, Las Eras in the Canary Islands.

Figure 1.50 Metamorphosed hornfels showing randomly orientated metamorphic minerals.

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