Exploring Geoscience Across the Globe - England

Chris King

with Elizabeth Devon, Peter Kennett, Pete Loader and Maggie Williams

International version approved by:
the International Geoscience Education Organisation
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for the teaching of the International Geoscience Syllabus

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International Geoscience Education Organisation

Contents

Purpose of the book

The book has been produced to support teachers across the world in teaching the International Geoscience Syllabus (reproduced in the Appendix). The syllabus covers the geoscience that all 16-year-old students should know and understand, as recommended by the international geoscience education community.

The structure of chapter headings in the book directly reflects the syllabus. The text has been written in language as simple and as jargon-free as possible, to make it widely accessible to teachers who want to use it in their teaching. Much of the exemplification is presented in tables and illustrated by photographs, so that the examples do not interfere too much with the blocks of text.

Material additional to the syllabus is presented in 'interest boxes', to give extra dimensions of interest and impact and to provide short case studies, but it is not expected that students would be introduced to all this additional material.

The original text was written as an 'international version' called '**Exploring Geoscience – across the Globe**' illustrated by photographs selected from across the globe and 'interest boxes' of global interest. Geoscience educators across the globe were invited to take this core text and to add photographs and 'interest boxes' for their own regions; they have also been asked to translate the text, as appropriate, to produce an '**Exploring Geoscience**' textbook for their own regions.

This '**Exploring Geoscience – across England'** is one of the regionalised versions of the textbook, with many photographs from England replacing the international ones and many added 'Interest boxes' for England.

The '**Exploring Geoscience – across the Globe**' textbook is keyed into a separately published '**Exploring geoscience across the globe – activities and questions**' book, giving details of a wide range of teaching activities related to each section and providing questions to test the knowledge and understanding of the students. The 'Activities and questions' book is linked in turn to a '**Exploring Geoscience across the Globe – activities and questions: some answers'** book available only to teachers.

All the books are published on the International Geoscience Education website at:
http://www.igeoscied.org/teaching-resources/geoscience-text-books/.

The International Geoscience Syllabus is published at: http://www.igeoscied.org/?page_id=269

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The original text and many diagrams for '**Exploring Geoscience – across the Globe**' were produced by Chris King (chris@earthlearningidea.com); some of the diagrams were redrawn from other sources. Other diagrams and photographs were sourced directly from copyright-waived areas of the internet. Most of the diagrams were redrawn by Tanja Reinhardt (reinhardtt2@ukzn.ac.za) of the University of KwaZulu, Natal, South Africa, who kindly designed the book and its covers.

We are very grateful to Wikimedia Commons (https://commons.wikimedia.org/wiki/Main_Page) as the source of many of the photographs and some of the diagrams under copyright-waived conditions. They have contributed greatly to the exemplification in the book. We are also grateful to the Earth Science Education Unit (ESEU: http://www.earthscienceeducation.com/index.html) for providing images.

The ‘**Exploring Geoscience across England’** textbook has been greatly enhanced by the wonderful source of images on the *Geograph* website at: https://www.geograph.org.uk/. The authors are hugely grateful to those who had the vision to set up the website and all its dedicated contributors.

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This ‘**Exploring Geoscience – across England’** version has photographs and ‘interest boxes’ contributed by Elizabeth Devon, Peter Kennett, Pete Loader and Maggie Williams to whom we are most grateful. These parts of the ‘**Exploring Geoscience – across England’** have been checked by Elizabeth Devon, Peter Kennett and Maggie Williams to whom many thanks. We are also most grateful to Anthony Tibbs for his formal proof-reading. Any remaining errors remain mine alone.

The ‘**Exploring Geoscience – across the Globe**’ textbook has been approved by the International Geoscience Education Organisation, the International Union of Geological Sciences through its Commission on Geoscience Education and Technology Transfer, and the European Geosciences Union, for the teaching of the international geoscience syllabus, and we are most grateful for their support and encouragement.

Chris King.

0 Why explore geoscience?

Geoscience is the scientific study of our whole planet. Nowadays, it is even more than that, because it includes planetary geology too. It involves the many elements of geology, such as geochemistry, geophysics, palaeontology, hydrogeology and engineering geology, but is wider, because it also includes meteorology, oceanography, environmental science, soil science and study of the solar system. Geoscience uses evidence from the planet's past and present to predict the future, but also uses evidence from the present to 'predict' what happened in the past. It focuses elements of biology, chemistry, physics, maths, geography and engineering into a study of the Earth and the planets.

One of the joys of studying geoscience is that everyone can do it. When children pick up interesting pebbles on a beach and begin to think why they are interesting, they are starting to ask the questions that geoscientists ask. When they collect several interesting pebbles, or different colours of sand, or different fossils, they are beginning to sort things out, or to classify Earth materials, as geoscientists do. When they ask why the sand forms interesting shapes, they are beginning to investigate Earth processes, just like geoscientists.

Figure 0.1: Interesting pebbles and sand shapes

Pebbles on the beach, Otter Estuary, Devon

Beach ripple marks, West Kirby, Wirral, Merseyside

If you want to study geoscience further, you might be able to do this at school or college or by taking a university degree. Many people study geology just because they enjoy asking and answering questions about how the Earth works, or because they enjoy collecting interesting things. But others become professional geologists, spending their whole lives asking and answering geoscience questions. They investigate the Earth, from the tropics to the poles, from the highest mountains to the deepest seas, or by searching for new Earth resources, better ways of disposing of waste or the best places to build new buildings and to live safely.

This is what this book is about. It begins by looking at the whole Earth system, the Earth within the solar system and how all this has changed over time. It brings together studies of the Earth's geosphere, hydrosphere, atmosphere and biosphere and looks at where the resources and power supplies we need are found. It focuses on Earth hazards and environmental issues and how these change human history and it explains what geoscientists do and how.

So, if all this interests you, read on – you will already be starting to think like a geoscientist.

Box 0.1E. Localities mentioned in the English 'interest boxes' in this book

1 Earth as a changing system

A system is made up of a range of different parts, linked together into a network that keeps the whole system working. Systems may be simple, like a washbasin; water enters the washbasin (is input) by the taps and flows out (is output) through the drain. The water can be hot or cold, so the heat energy of the water (its temperature) is also one of the inputs. The heat from hot water can be lost when the water goes down the drain, but can also be output as the water in the basin cools down. The washbasin system has a boundary which is the sides and base of the basin. Inputs come in from the outside environment and go out to the surrounding environment, beyond the boundary.

The washbasin is an example of an **open system**, with interactions with the outside environment at the boundary. In the washbasin example, water and heat are inputs and outputs to the environment. An example of a **closed system** is a vacuum flask; when the top of the flask is on, liquid cannot enter or leave the flask and heat cannot enter or leave the flask either. No system can be completely closed, so even the best vacuum flask will lose heat from a hot liquid inside over time.

Figure 1.1. A washbasin and a vacuum flask, examples of open and (nearly) closed systems

The Earth system is not only extremely complex, much more complex than these simple examples, but it has many subsystems and has changed and is changing over time.

1.1 Attributes

The Earth is an open system to energy. Most of the energy that drives the Earth's subsystems is received as radiation from the Sun. This energy is an input to the Earth during the day, but some is radiated back out to space as an output during the day and at night. Since the radiation input and output are generally in balance, the Earth's overall temperature remains steady, at least in the short term.

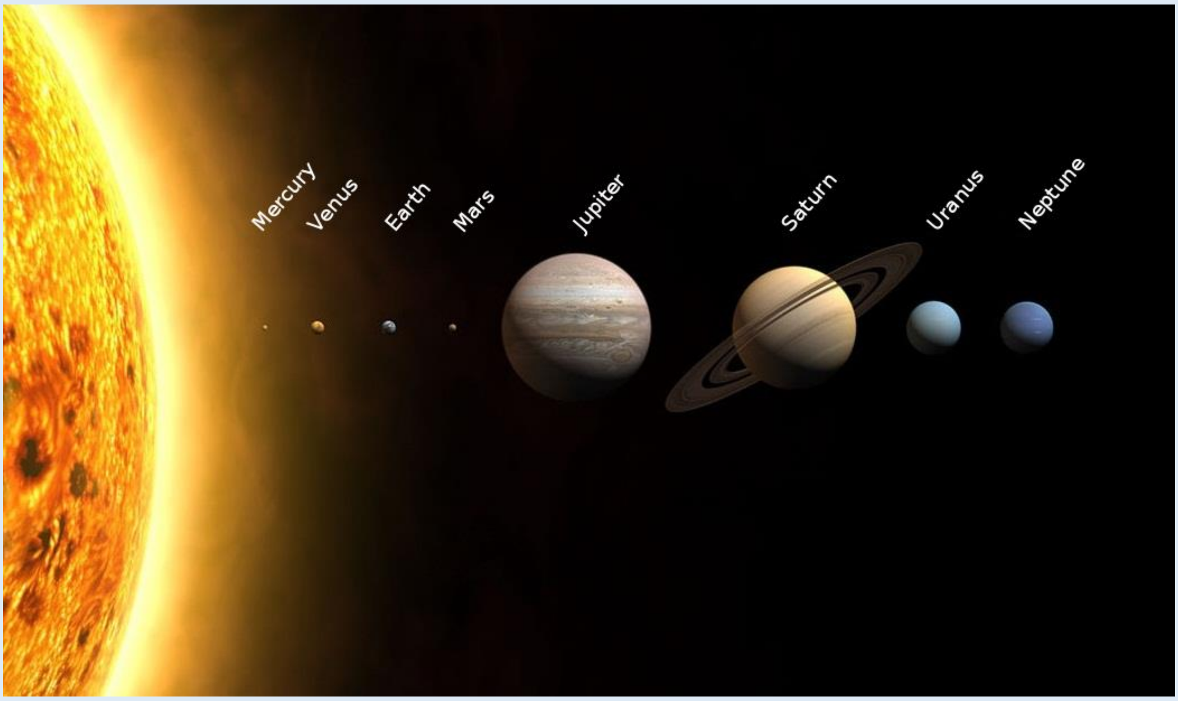
Figure 1.2. The Earth – a very complex system

However, the Earth is nearly a closed system to matter today. This was not always so, since the early Earth was bombarded by asteroids. Nowadays, what is on the Earth stays on the Earth; little material, compared with the size of the Earth, is added by meteorites and cosmic dust, and the only dense material lost to space is in space probes.

Earth's system has changed over time, not only because the amount of bombardment has reduced but also because of a range of other changes, such as the cooling of the Earth, the formation of oceans, the evolution of the atmosphere and life, and plate tectonic effects.

The Earth system is part of the solar system. This is also nearly a closed system, to both energy and matter – since very little energy is received from starlight and very little matter is received either.

Box 1.1. The matter of the solar system, shown to approximate size (but not distance) scale



This 'portrait' of the solar system shows the Sun and the planets. The sizes are shown in the correct proportions – but the distances apart are not. This diagram shows most of the matter of the solar system. Not included (because they are too small) are the Moons, dwarf planets, asteroids, comets and dust.

The Earth system can be divided up into four main subsystems: the solid Earth (the **geosphere**), the air around the Earth (the **atmosphere**), the water on the planet (the **hydrosphere**) and life on Earth (the **biosphere**).

The **lithosphere**, which forms the Earth's tectonic plates, is the outer part of the geosphere.

1.2 Interactions

The geosphere, hydrosphere, atmosphere and biosphere are very open systems because they all interact, exchanging both energy and matter. Interactions between these four subsystems go on everywhere, all the time, acting over very short to extremely long timespans. It is these interactions that make our planet so dynamic. Wherever you go, whatever you do, these systems will be interacting all around you at different rates, from very fast to extremely slow.

Riverbanks are good places to see Earth system interactions. River flow is part of the hydrosphere, eroding banks and transporting the sediment of the geosphere. Biosphere animals and plants live on the banks, photosynthesising and respiring atmospheric gases. Water rises into the atmosphere through evaporation of river water, transpiration of plants and breathing of animals. This water vapour can later fall as rain, contributing atmospheric water back onto the geosphere again.

Box 1.2. The local water cycle, an example of geosphere, hydrosphere, atmosphere, and biosphere interactions

Raindrops, when they first form, contain neither acid nor alkali and so are neutral. However, as they fall through the atmosphere they dissolve carbon dioxide and so become slightly acidic. When rainwater lands on soil, it sinks in. Many animals live in the soil and they respire, taking in oxygen and releasing carbon dioxide. This extra carbon dioxide dissolves in the soil water, making it even more acidic. Decaying plant material adds humic acid to the water too. The acid water reacts with rock fragments in the soil, dissolving limestone particles and breaking down particles of other rocks. Through these reactions, the water becomes neutral again so that, when the water comes out of the ground in springs, it is usually neutral.

Rainfall, May Hill, Gloucestershire

Soil moisture

Groundwater spring near Bradford, Yorkshire

This example highlights how the different Earth systems interact. Hydrosphere raindrops dissolve carbon dioxide from the atmosphere. They sink into the soil of the geosphere where they dissolve more carbon dioxide produced by the animals of the biosphere. The acidic soil water reacts with rock fragments of the geosphere becoming neutral and trickling out of springs, where it is visible hydrosphere again.

In this example, matter is exchanged (including water, atmospheric carbon dioxide, the inputs and outputs of respiration and reaction with rock fragments) and so is energy (including from the falling rain, the energy of respiration and the chemical energy involved in water/rock reactions).

1.3 Feedback

Feedback is a vital part of systems. A simple example of feedback is a water boiler with a thermostat (a thermometer with a switch). When the water becomes cool, the thermometer feeds back this information to the switch and the boiler is switched on. When the water becomes hot, this information is fed back to the switch by the thermometer, and the boiler is turned off again. Our bodies have similar feedback mechanisms – when we get too hot we sweat to cool down, but when we get too cold, we shiver to warm up.

Feedback systems can be **positive** or **negative**, but these can be confusing terms. Negative feedback keeps systems in a stable state and so is a good thing, whilst positive feedback can make a system unstable, with devastating results.

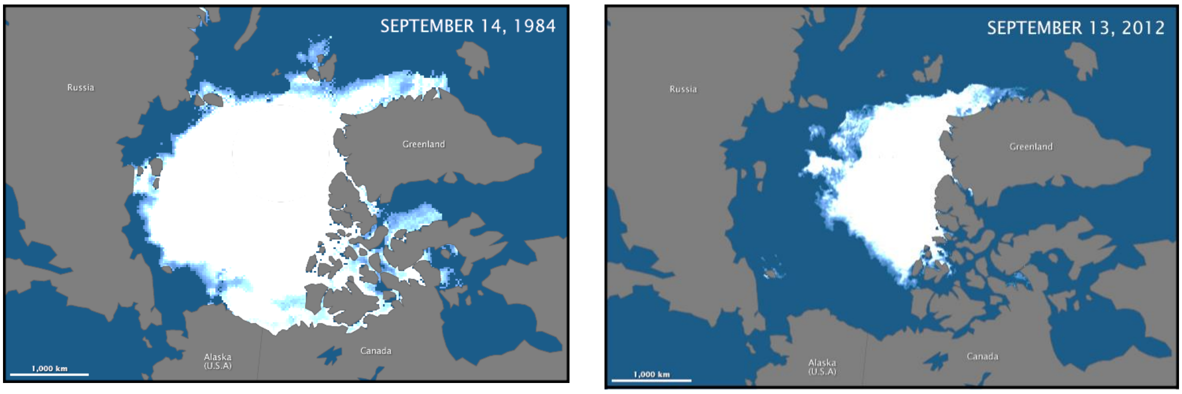
For example, the amount of salt in the oceans is affected by a negative feedback system. Rivers around the world dissolve salt (sodium chloride, NaCl, the mineral halite) from the surrounding rocks and carry it to the sea, but the saltiness (salinity) of the oceans stays the same (around 3.4% salt) when we would expect it to become more and more salty over time. The negative feedback system that removes the salt happens when areas of seawater become trapped in coastal basins. As the seawater evaporates, salt is deposited and can become buried as a sedimentary rock, so removing it from the oceans.

Figure 1.3. Salt being extracted from a coastal salt lagoon in Tunisia

The negative feedback systems in our own bodies keep everything stable. These processes working together in living things are called homeostasis.

When there is positive feedback, the system can become unstable. When sunlight hits ice sheets, most of it is reflected and so there is little warming effect on the Earth. The reflection of sunlight by pale-coloured surfaces like ice is called **albedo**. This reflection of sunlight is one of the factors that keep Earth's temperature stable. However, positive feedback can have an effect in two different directions. If Earth becomes cooler, the ice caps grow, increasing the albedo effect, so causing the Earth to become even cooler; this could trigger an ice age. But, if the Earth becomes warmer, the ice caps will melt, reducing the albedo reflection, so causing the Earth to become even warmer. Eventually the ice could melt completely, moving the Earth into a much warmer state.

Figure 1.4. The Arctic ice in 1984 and 2012. In the past, the large area of floating ice had a large albedo effect. As Earth has become warmer, the area of ice has become smaller; this has reduced albedo and contributed to the warming of the Earth, through positive feedback.



When there is positive feedback in a system, this may continue until a '**tipping point**' is reached and the system tips over into a new steady state. In the past, the Earth has had a cold steady state, when parts of the Earth were covered with ice ('**icehouse conditions**') and a warm steady state when there were no ice sheets ('**greenhouse conditions**').

1.4 Processes and products

1.4.1 Cycles

Fill a mug with boiling water and leave it for a minute or so for the mug to warm up. Then pour out the water and add about 1 cm depth of boiling water to the mug, invert a glass tumbler on top (as shown in Figure 1.5) and watch what happens

You will see the glass tumbler becoming cloudy as water condenses on the inner surface, then trickles of water running down into the mug.

What happens is that water evaporates from the surface of the hot water to become invisible water vapour in the air inside the mug/tumbler. Then the water vapour condenses as droplets on the insides of the cooler tumbler, making it cloudy, until the drops become large enough to flow down, back into the mug.

What you see is a combination of processes and products. The process of evaporation produces a product of water vapour gas. The process of condensation produces a product of small droplets of liquid water on the inside of the tumbler. The process of flow then carries the water back into the mug – this new product then becomes added to the liquid water in the mug.

Figure 1.5. A simple water cycle demonstration

Processes cause something to happen; **products** are the results.

This is a simple version of a cycle. In this case, the water begins in the mug as liquid water, evaporates to water vapour, and then condenses to water droplets which join together to flow downwards into the mug again. This is also a simple system, which is closed for water (water does not leave or join the system).

All Earth materials are cycled in some way. Important examples include the water, carbon and rock cycles.

1.4.2 The water cycle

The natural **water cycle** is more complex than the mug and tumbler demonstration in Figure 1.5, and water cycle processes and products are around us all the time.

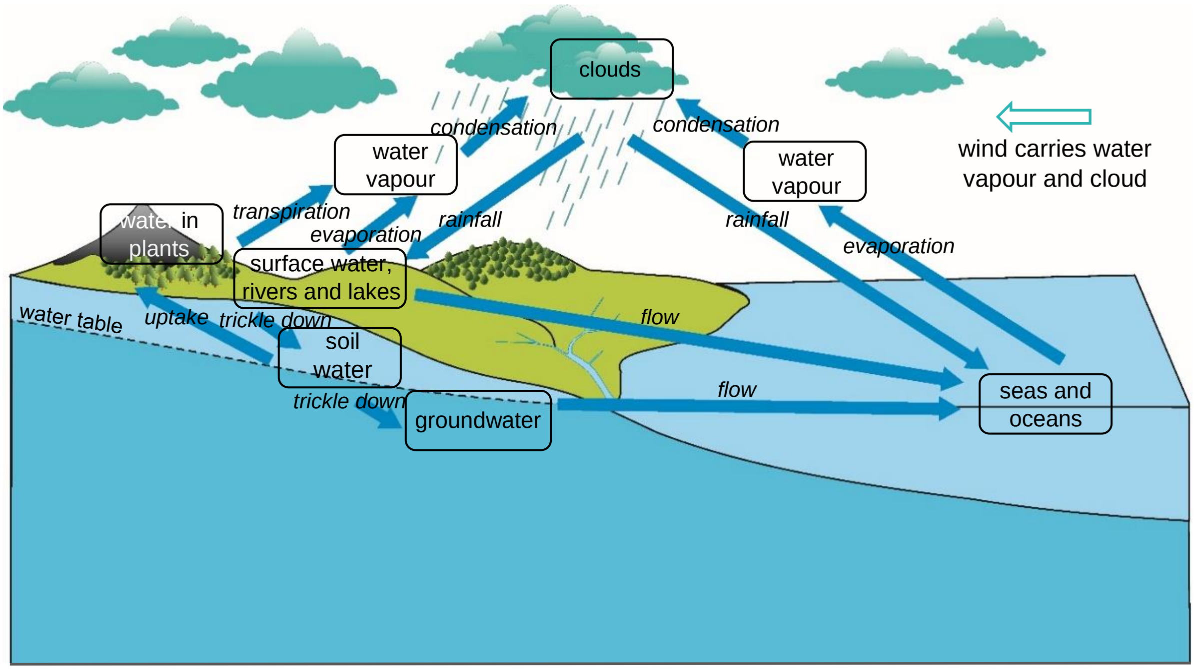
When it rains, water forms puddles on the ground. The puddles later evaporate into invisible water vapour in the air. When the air cools, the water vapour condenses into water droplets as clouds. As clouds continue cooling, the water droplets join together to form raindrops which, when they are large enough, fall as rain. Even this simple outdoor system is complicated by many more factors. Condensing water vapour produces not only clouds, but mist and fog as well. Water falls from clouds as rain, but also as snow and hail. Water that reaches the ground does not just form puddles, but often flows into gutters, streams, rivers and eventually lakes and the sea. Water evaporates from all these water cycle products all the time, whilst plants **transpire**, releasing the water taken in by their roots into the air, as water vapour through their leaves. The water vapour from evaporation and transpiration is carried to different areas by air currents.

Some rain and river water percolates downwards into the soil and rock beneath and becomes part of the groundwater in the pore spaces of porous rocks. This water flows downhill through permeable rocks underground and eventually flows out in springs.

In cold regions, water falling as snow can build up into the ice of glaciers and ice sheets, while groundwater can be frozen in **permafrost** (permanently frozen ground). Ice can also flow, or melt to become liquid water again.

The main water cycle processes are evaporation, condensation, lateral movement by air (wind), falling (of rain, etc.) and flow over or beneath the ground. In cold areas freezing, melting and flow of ice are important too. Many of these processes and products are shown in Fig. 1.6.

Figure 1.6. Water cycle products (in boxes) and processes (*in italics*).



Box 1.3. Part of the water cycle near your home

You can see part of the water cycle in action near your own home. Raindrops from rainclouds fall into puddles; the water runs down gutters and eventually reaches lakes. Evaporation from lakes and other areas of water, produces invisible water vapour in the air. When this cools, it condenses to form the clouds which produce rain.

1.4.3 Fluxes, stores and residence times

The processes and products of cycles are also called fluxes and stores. **Fluxes** are the flows of materials through the processes, measured as flow rates. Water cycle fluxes range from the very quick (such as water flows in flooded rivers) to the very slow (the flow of ice sheets) and from the very large (global evaporation rates) to the very small (snowfall onto ice sheets). **Stores** are the products; water cycle products also range from the very large (the oceans) to the small (the water stored in your own body). **Residence times** are the amounts of time it takes for a store to be replaced. Some residence times are short, such as the time that water vapour is stored in the atmosphere, of only a few days. Other residence times are very long, such as the tens of thousands of years of storage of ice in polar ice sheets.

1.4.4 The rock cycle

The surface part of the rock cycle is closely linked with the water cycle. Flowing water removes and carries sediment. In still water, sediments are deposited and can build up into thick sedimentary sequences. Sediments become lithified into sedimentary rocks, usually deep underground. If these rocks are uplifted and the materials above are removed, they become exposed at the Earth's surface, ready for the cycle to begin again.

Box 1.4. Part of the rock cycle somewhere nearby

You can see parts of the rock cycle in action whenever the wind blows or water runs over the land. Blowing wind picks up, carries and deposits dust, leaves and litter; so does running water. Running water on this sand bank has removed sand from the small channels at the top of the photograph, carried it down the bigger channels and deposited it in small deltas at the bottom, all in a small area of beach, only around a metre across.

This sedimentary part of the rock cycle becomes more complex when rocks become involved in mountain-building episodes. The enormous temperatures and pressures cause folding and fracturing (faulting) and may also change the rocks into metamorphic rocks.

The changes can go further if the temperature increase causes rocks to partially melt, forming liquid rock, or magma. Magma is less dense than the surrounding rock, and so rises. Either it cools down and solidifies slowly underground, or it is erupted at the surface through volcanic activity. All rocks formed from magma are igneous rocks. All the buried rocks can be uplifted and exposed to become part of the rock cycle again.

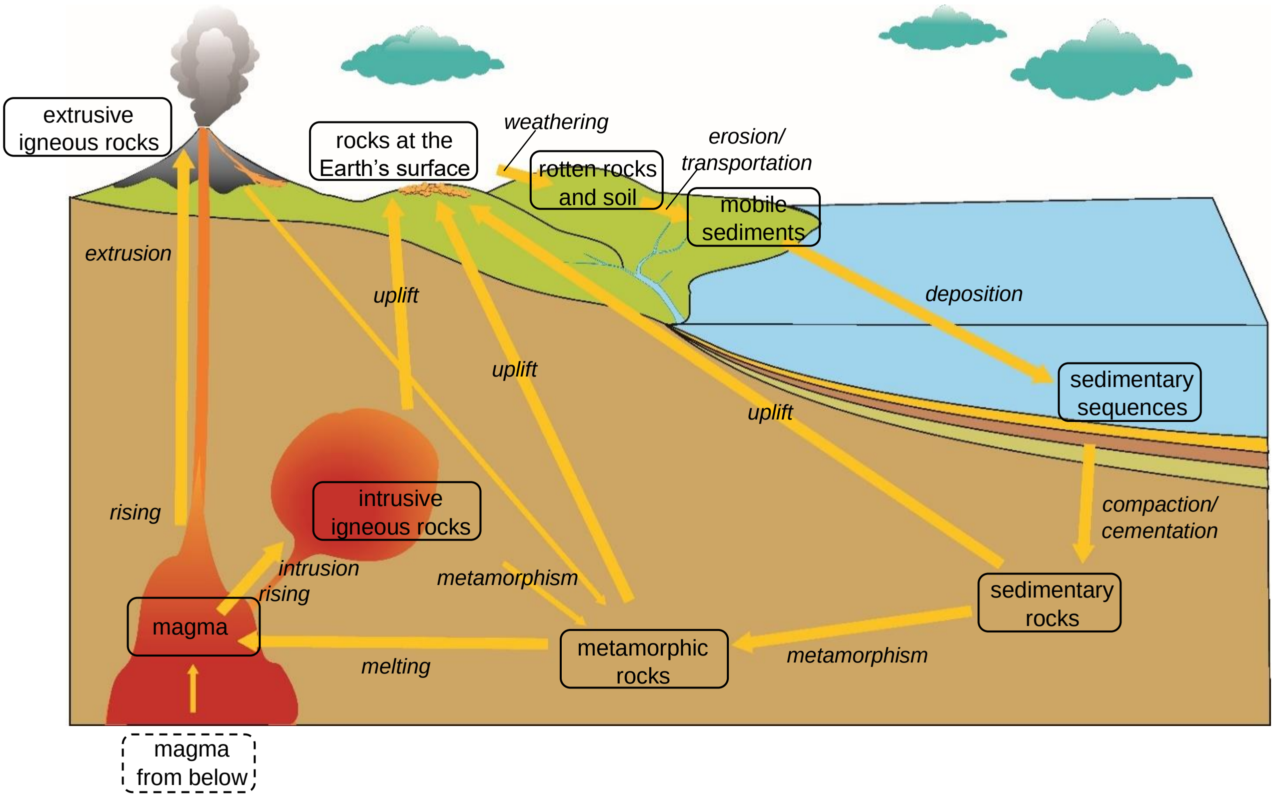
Figure 1.7. shows how the rock cycle products (in boxes) and processes (in italics) are linked together. Rocks at the Earth's surface are changed by weathering into rotten rocks and soil; when this material is eroded and transported it becomes mobile sediments. Deposition of mobile sediments builds up sedimentary sequences. These can be changed by compaction/cementation into sedimentary rocks which can then be uplifted to become rocks at the Earth's surface again. However, they can also undergo metamorphism to become metamorphic rocks, which can then be uplifted to become rocks at the Earth's surface as well.

Metamorphic rocks can become melted to liquid magma which may rise through intrusion to form intrusive igneous rocks (which can then be uplifted to become surface rocks) or the magma can be extruded volcanically as extrusive igneous rocks. Magma can also be added to this system from below, whilst igneous rocks may also undergo metamorphism.

In the rock cycle system, the products or stores are the sedimentary, metamorphic and igneous rocks. The processes causing the flows or fluxes between these stores are metamorphism, melting, solidification and all the processes involved in the removal, movement, deposition and **lithification** (change of sediment into sedimentary rock) of sediment. The residence times of the rocks are usually millions of years.

This simple view of the rock cycle is more complex in detail, as explained beginning at section 4.1.2.

Figure 1.7. Rock cycle products (in boxes) and processes (*in italics*).



1.4.5 The carbon cycle

When you breathe, you breathe out more carbon dioxide than you breathe in. This is because one of the body processes is respiration, where oxygen reacts with carbon compounds in the cells of your body, releasing energy and producing carbon dioxide. The respiration process releases a flux of carbon dioxide into the atmosphere, which stores a small amount of carbon dioxide all the time (about 0.04%). All animals release carbon dioxide through respiration, and they also release carbon compounds into the atmosphere through excretion and when they die and decay.

The residence time of carbon dioxide in the atmosphere is short because it is removed quickly, mostly by the photosynthesis of plants. In the photosynthesis process, energy from sunlight causes carbon dioxide to react with water to form the carbon compounds that make up plants. So the Earth's plants, particularly the algae in the oceans, form a large store of carbon. This carbon is released when they die (or through being eaten by animals), or when land plants are burnt, either deliberately or through wildfires.

Box 1.5. The carbon cycle in action.

As these people are admiring the view over Poole Harbour in Dorset. They are respiring and breathing carbon dioxide into the atmosphere. Meanwhile the green plants are photosynthesising in the sunlight, taking in carbon dioxide and building it into new plant cells. If the people ate lunch, this process would be part of the carbon cycle too. These carbon cycle fluxes (flows) happen wherever on Earth there are animals and plants, including those outside your window.

This is the **short carbon cycle**, as studied by many biologists. It involves photosynthesis and respiration, egestion and decay. This seems to be a balanced cycle, with as much carbon being added to the atmosphere as is removed. However, there are much longer parts of the carbon cycle as well; for example, some of the carbon dioxide from the atmosphere can become dissolved in the ocean, with residence times of thousands of years.

Some animals and plants contain ‘hard parts’ made of calcium carbonate. The chemical formula for calcium carbonate is $CaCO_3$ and the second ‘C’ in the formula is carbon, which makes up some 12% by mass of calcium carbonate. Your bones and the bones of most animals contain calcium carbonate. Shells are made of calcium carbonate and some microscopic plants also contain calcium carbonate. When these animals and plants die, parts of them are deposited as sediment and can become part of sedimentary rocks, with residence times of millions of years. The calcium carbonate-rich rock made mostly of marine animal remains is called limestone; the rock made mostly of microscopic calcium carbonate plant remains is chalk.

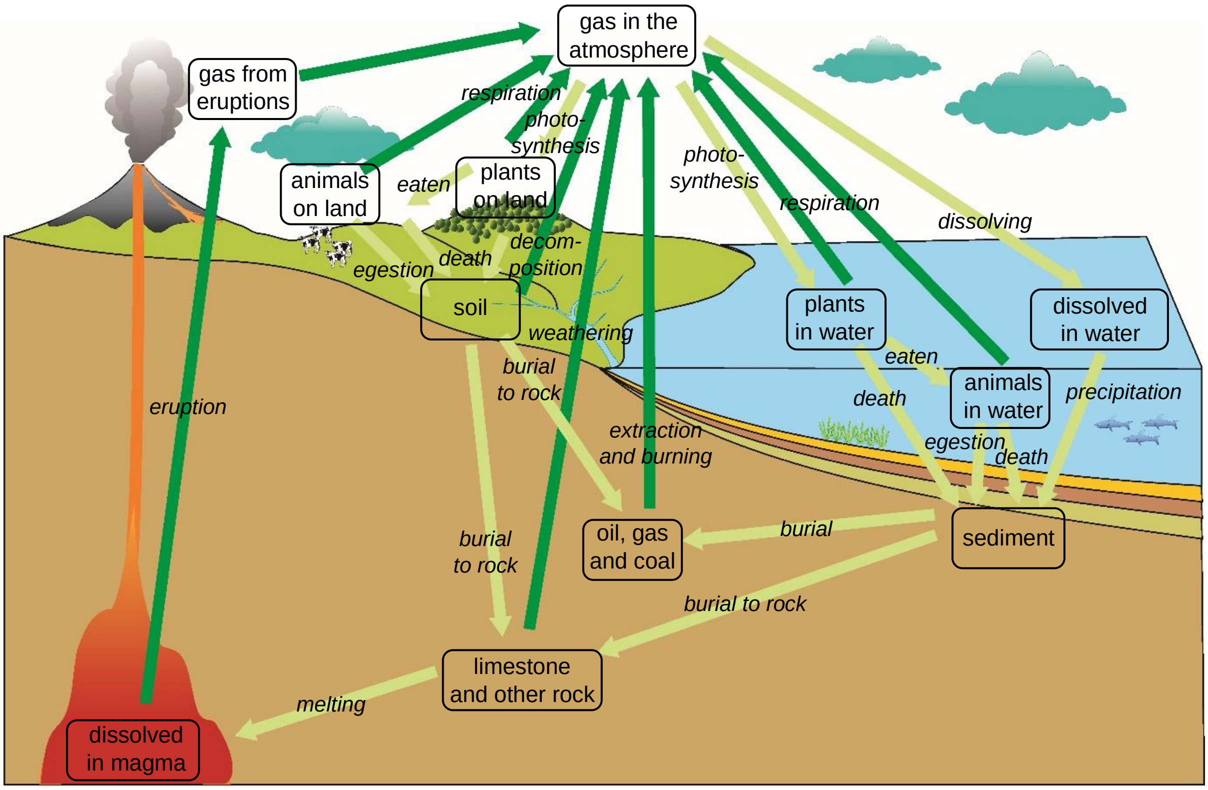
When plants die, they usually decay, but if they are buried by sediments and preserved, the carbon in them is also preserved. When land plants are preserved, thick layers can form coal, releasing natural gas as it matures. As microscopic animals and plants in the oceans die, they can also be preserved in sediment, and later be changed to oil and natural gas. Natural processes release these stores of carbon back to the atmosphere over millions of years; oil and gas can leak to the surface and coal can be brought to the surface by uplift and removed by surface processes.

Sedimentary rocks containing limestone, chalk, coal, oil and natural gas can become involved in mountain-building episodes and metamorphosed or even partially melted. Then the magma produced by partial melting will contain dissolved carbon, which may be brought to the surface and released in volcanic eruptions. Many eruptions release enormous quantities of carbon dioxide gas into the atmosphere.

These longer-term parts of the carbon cycle also seem to be in balance. However, human activities may be changing this balance, by removing and burning coal, oil and natural gas. This is explained in Section 4.3.3.

The processes and products of the short and longer carbon cycles are shown in Figure 1.8.

Figure 1.8. Carbon cycle products (in boxes) and processes (*in italics*) – processes 'fixing' carbon are shown by pale green arrows, processes releasing carbon by dark green arrows.



1.5 Energy sources

Sunlight provides the energy for photosynthesis, and is the original source of most of the energy that drives the water cycle and the surface processes of the rock cycle.

In the carbon cycle, some of the energy stored in plant cells built through photosynthesis can be released when animals eat the plants. This provides energy for all plant-eating animals on Earth; predators then get their energy from eating other animals. Some of this energy can be stored in buried plant and animal remains, to be released by natural processes or human activity later. Only the uplift, metamorphic and igneous processes of the carbon cycle are driven by energy that did not originate in the Sun; they are driven by Earth's internal energy.

Energy from the Sun causes evaporation as part of the water cycle. Water vapour is also released into the atmosphere by plant transpiration, and plants could not exist without photosynthesis. Energy from the Sun also causes air movement; air rises over warmer areas and sinks in cooler areas, producing the horizontal air movement that we call wind. Water vapour from areas of strong evaporation or transpiration is carried elsewhere by wind action. The main parts of the water cycle that do not depend on energy from the Sun are the downflow of cooling air under the Earth's gravity and the circular motion of currents in the atmosphere and ocean resulting from the spin of the Earth.

In the rock cycle, the Sun's energy is important in breaking up rock and soil at the Earth's surface. The Sun-driven parts of the water cycle that move and deposit sediment involve water and ice flow, whilst Sun-driven air movement also carries sediment. The parts of sediment movement that are not driven by the Sun are the downward movement of rocks, water, ice and air currents under Earth's gravity and the compaction of sediments by overlying materials, again due to gravitational effects.

The interior of the Earth contributes very much less than the energy Earth receives from the Sun. Nevertheless, Earth's internal energy sources have vital effects, particularly when they act over geological time.

Some energy has remained in the core from when the Earth was entirely molten, soon after it first formed; this primeval energy is still being released slowly. Another important source of energy is radioactive decay in the solid parts of the Earth, deep below the surface. Earth's internal energy drives the internal parts of the rock cycle, resulting in the lithification of sediments, faulting (causing earthquakes), folding, metamorphism, uplift and the partial melting that causes igneous activity.

So, most of the energy affecting the Earth comes from the Sun. Other energy sources are the primeval energy and energy from radioactive decay, described above. In addition, there are gravitational potential energy and rotational kinetic energy. The gravitational pull of the Sun, Earth and Moon and the rotation of the Earth, the orbiting of the Moon around the Earth, and the Earth and Moon together orbiting around the Sun, are converted into thermal energy, called 'tidal heating'.

2 Earth is a system, within the solar system within the universe

2.1 Origins

Although the speed of light is enormous at nearly 300,000 $kmsec^{-1}$ (travelling 300,000 kilometres every second), it still takes 8 minutes for the light from the Sun to reach us and several years for the light from nearby stars to reach our eyes. So looking into the night sky means we look back in time. With powerful telescopes we can see galaxies, or cosmic 'islands' of billions to hundreds of billions of stars, as they looked in the distant past. Our studies have shown that the universe began about 14 billion years ago. At the start there were no stars or galaxies but the whole universe was filled with highly energetic radiation. In the '**big bang'** the universe began expanding and the radiation was changed into matter.

The most common type of matter is hydrogen – the simplest atom. However nearly everything on Earth and beyond, including our own bodies, is made of other types of atoms which were first formed in the cores of stars. As the matter of the universe cooled down, stars began to form and group together into galaxies. The energy that drives stars, including our Sun, comes from hydrogen atoms joining (fusing) together to make larger atoms. So, in the cores of stars, atoms which are abundant on Earth, like silicon, oxygen, carbon, nitrogen and iron began to form. Over time, stars blasted a lot of matter into space, including these newly-formed atoms. So, around 4.6 billion years ago, the solar system of our Sun began forming from the original hydrogen and the 'ashes' of former stars. Our Earth's system is a part of our solar system.

Figure 2.1. Galaxies photographed by the Hubble telescope. Colours have been added, based on the data collected, to highlight key features of the images.

Box 2.1. The universe from your own garden or park.

You can see the stars of the universe, and some of the planets of the solar system, from your own garden or park, but you will be able to see much more if you go to a country area nearby on a Moonless night, where there are no street or other lights. As your eyes become accustomed to the darkness, more and more stars will appear. Stars twinkle, but if there is a planet in view, it will shine with a steadier light. If you see a light moving steadily across the sky, that is a satellite reflecting the Sun. If it is really dark, you might be able to see a band of stars arching overhead; this is the Milky Way, the stars of our own galaxy, which you are seeing edge-on. If you have a camera with a shutter that can be left open and you stand it on a stable place, you will be able to capture these sights of the universe. Leaving the shutter open for an hour or more, will also capture how the stars seem to arc through the sky as the Earth spins.

Box 2.1. The universe from your own garden or park, continued.


A chapel in France under the Milky Way

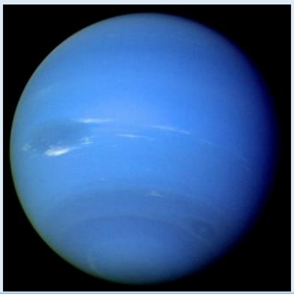

Star movement caught by an open shutter, Chile

Our solar system contains the eight planets, shown in Table 2.1.

Table 2.1. Planets of the solar system, in order from the Sun

Name	Image **(not to scale)**	Distance from the Sun, million km	Diameter, km	Mass, 10^{24} kg	Mean surface temper-ature, °C	Other features
Mercury		57.9	4879	0.33	167	• No Moons • Cratered surface • Solid terrestrial planet
Venus		108.2	12,104	4.87	464	• No Moons • Covered by cloud • Cratered surface • Solid terrestrial planet
Earth		149.6	12,756	5.97	15	• One Moon • Oceans • Some craters known • Solid terrestrial planet • Plate tectonics identified

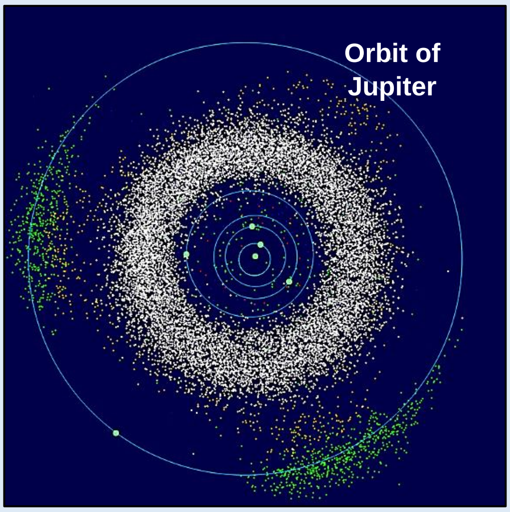
Table 2.1. Planets of the solar system, in order from the Sun, continued

Name	Image (not to scale)	Distance from the Sun, million km	Diameter, km	Mass, 10^{24} kg	Mean surface temper-ature, ºC	Other features
Mars		227.9	6792	0.64	-65	• 2 Moons • Cratered surface • Large volcano • Past sedimentary processes • Terrestrial planet
Jupiter		778.6	142,984	1898	-110	• 67 Moons • Ring system • Belts of cloud • Large red storm spot • Gas giant planet
Saturn		1433.5	120,536	568	-140	• 62 Moons • Ring system • Belts of cloud • Gas giant planet
Uranus		2782.5	51,118	86.8	-195	• 27 Moons • Ring system • Gas giant planet
Neptune		4495.1	49,528	102	-200	• 14 Moons • Ring system • Gas giant planet
Pluto is no longer considered to be a planet; it is one of the **dwarf planets**						

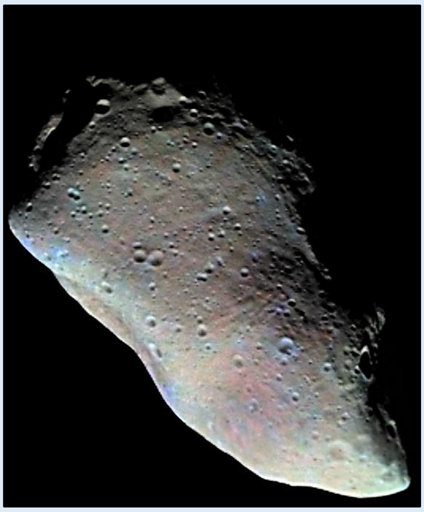
Our solar system not only contains planets and dwarf planets, but also belts of **asteroids** and **comets**. Many of the meteorites that hit the Earth and other planets originally came from the asteroid belt or from comets. Impacts from meteorites and larger bodies are one of the catastrophic events affecting the Earth and other planets over time; see section 3.4.

Box 2.2. The asteroid belt.

The main asteroid belt lies between the orbits of Mars and Jupiter, containing billions and billions of lumps of rock and stone. Some are rich in carbon, some in silicon and some in nickel-iron. The largest asteroid is nearly 1000 km across, but most are pebble-sized or smaller. Although there are many asteroids, they are so far apart that many spacecraft have travelled safely through them without any damage. While in other parts of the solar system space debris like this collided together to build up a planet, it seems that the nearby large planet of Jupiter affected this belt, stopping planet-build-up from happening.



The asteroid belt between Mars and Jupiter


Asteroid Gaspra photographed from the Galileo spacecraft

Box. 2.3. Comets.

Comets are icy bodies in the solar system that, when they get close to the Sun, release gases which often form a white tail. The tail flows in the direction of the solar wind, always facing away from the Sun. Many comets have enormous oval orbits that take them from deep space into the heart of the solar system and out again.


Hale-Bopp comet, 1997

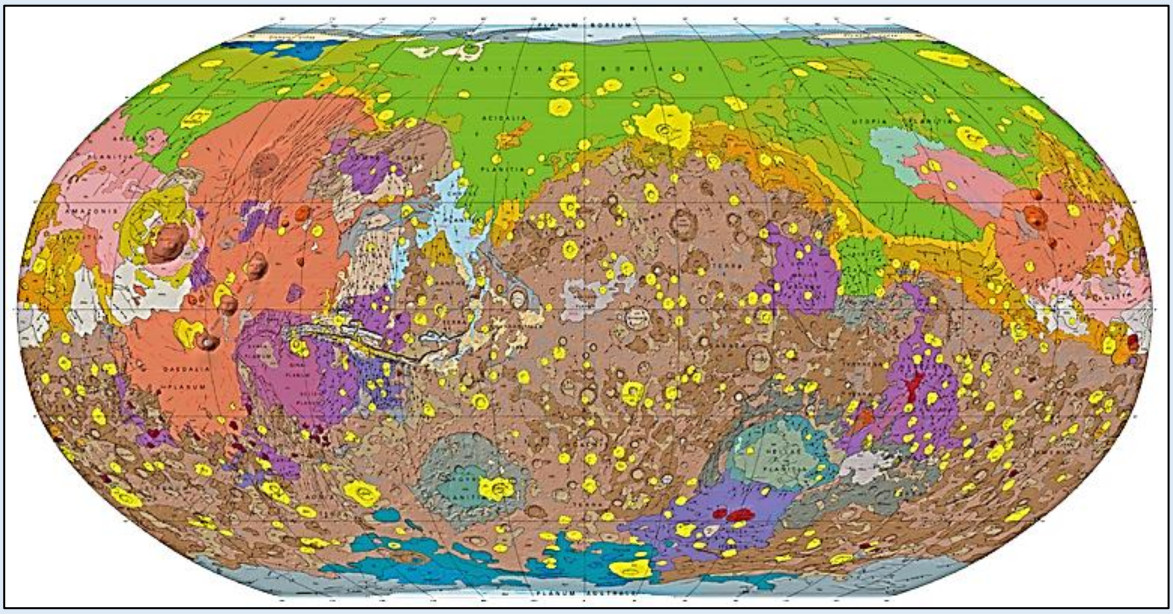

Comet Churyumov-Gerasimenko in September 2014 as photographed by the Rosetta spacecraft before the lander Philae landed on its surface

The only bodies in the solar system on which we have so far been able to land instruments safely are the Earth's Moon, the Churyumov-Gerasimenko comet, the planets Mars and Venus, and Saturn's Moon Titan.

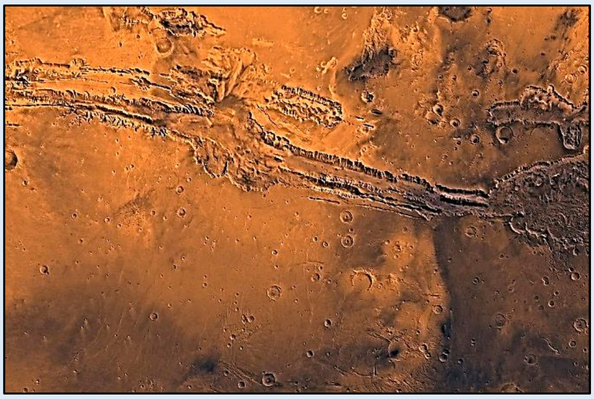
Box 2.4. Planetary geology – Mars

Before landing instruments on Mars, we already had a very good idea of the geology of the planet, since the geological principles that apply on Earth also apply on other planets. Observations from telescopes and orbiting satellites had shown a huge volcanic region covering 25% of the surface, including three enormous volcanoes, the largest volcanoes in the solar system (red and purple on the map). There were also very large craters produced by impacts, with raised rims and central depressions, the largest being 1800km across (yellow on the map). Near the equator there was a deep canyon system more than 4000 km long, formed by faulting in the distant past. Some parts of the surface had systems of valleys cut by flood water; more than 4000 water-formed valleys with lake beds and deltas have now been mapped.

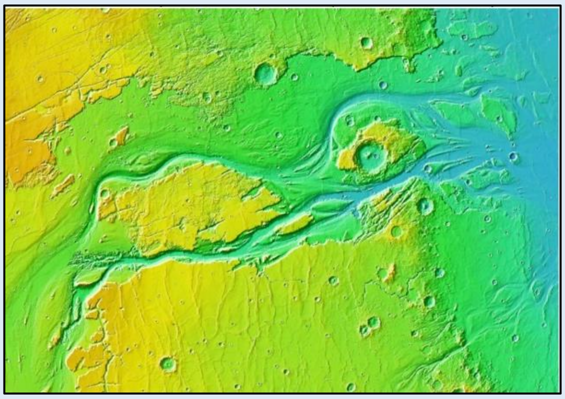
The landers have provided even more evidence of water flow, including sedimentary layers and rounded pebbles. The landers have also shown that most of Mars is cratered desert, covered by boulders and dust. Wherever the water is that used to flow over the surface, it is not there now.



Geological map of Mars. Green areas are lowland geology; reds and purples are volcanic rocks; blues are polar geology; brown and orange colours are highland rock areas; yellow are impact craters

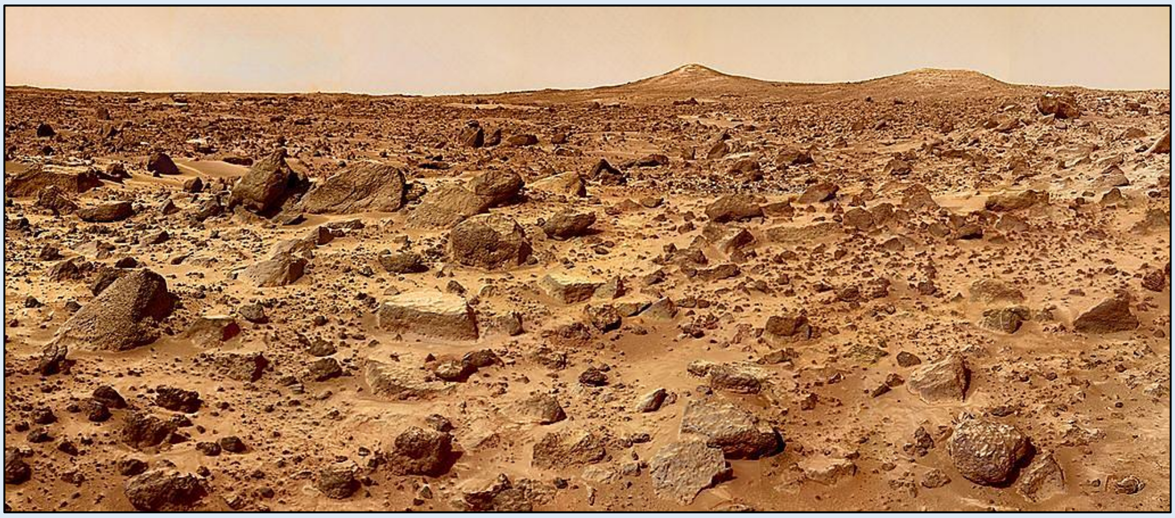


The faulted canyon system near the equator



The Kasei Valles outflow channel

Box 2.4. Planetary geology – Mars, continued



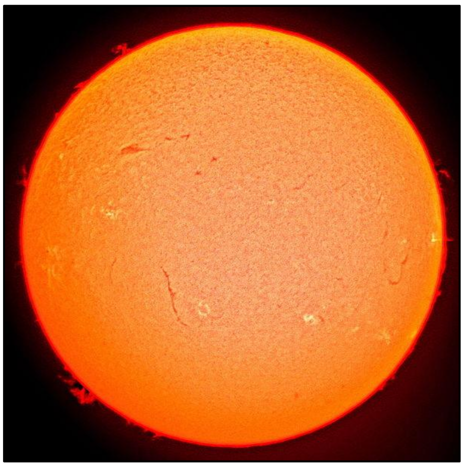
View from the Pathfinder site on Mars – foreground boulders and dust with low background hills

2.2 The Sun

The Sun is our star. It provides energy throughout the solar system and beyond.

Energy from the Sun passes through space, mostly as visible light, infrared and ultraviolet radiation. When this energy warms land and ocean surfaces, some of it is radiated back and warms the atmosphere. Energy is received from the Sun during the day and is radiated back out into space at night. These energy flows balance so that the temperature of the whole Earth stays the same on a daily basis. The space-based observations of the Sun's energy output that began in the 1970s show that this energy output changes according to several cycles, but only by around 0.1%.

Figure 2.2. The Sun – our main source of energy



2.3 Sun, Earth and Moon

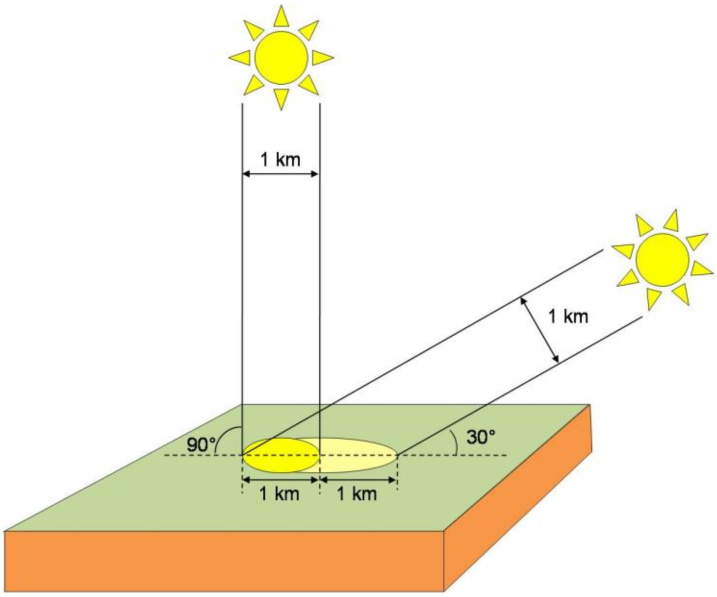
2.3.1 Day/night

Earth receives energy from the Sun as ultraviolet, visible and infrared radiation, which heats the Earth. The heating is greatest when the Sun appears highest in the sky, as shown in Figure 2.3. When the Sun appears directly overhead, a 1km-wide beam of radiation heats a 1km-wide zone of the Earth, but when the angle of the Sun is 30^{o}, a similar 1km-wide beam heats a 2km-wide zone of the Earth, so that half the amount of heating is received at each point.

Box 2.5. Changing shadows with the time of day.

When the Sun appears highest in the sky during the middle of the day, shadows are short. As the Sun sinks, shadows become longer. The changing position of the Sun in the sky is the result of the spin of the Earth. Here, the left-hand picture was taken at 12.00 noon, the middle one at 4.00pm and the right hand one at 6.00 pm in September in Sheffield, Yorkshire.

Figure 2.3. The heating effect of the angle of the Sun in the sky



Heating of the Earth takes time, so that the warmest part of the day is usually later than the time when the Sun is highest in the sky.

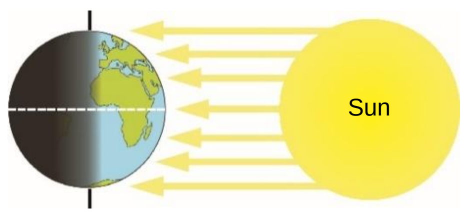
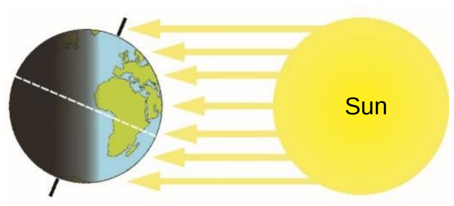
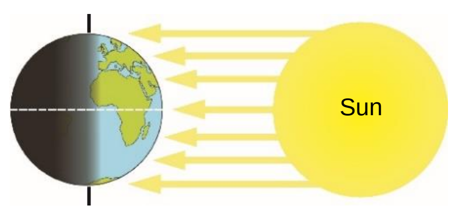
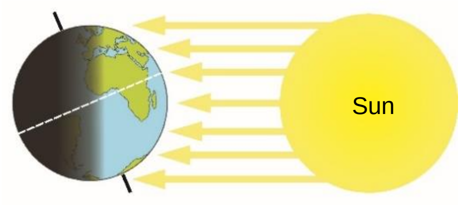
The amount of heat received depends on what the surface is like. Dark surfaces absorb and re-radiate more heat than pale-coloured surfaces, since the pale-coloured surfaces reflect more of the radiation; this is the albedo effect. Land heats up faster than water, because the water circulates the heat received into the depths of the water body. But land also cools down faster than water too – because the circulating water takes time to lose its heat. This means that if you live near a large area of water, temperatures will not rise as high as if you live a long way away from water, but they will not fall as low either. So coastal areas normally have more moderate temperature highs and lows than inland areas.

The Earth radiates the energy it has received during the day back to space as infrared radiation during the night. The coldest part of the night is usually soon after dawn, when the outgoing radiation begins to be balanced by the incoming radiation again.

2.3.2 The seasons

The heating effect of the apparent height of the Sun in the sky in Figure 2.3. affects the Earth's seasons, as shown in Table 2.2. The lengths of days and nights also have an important effect too.

Table 2.2. The tilt of the Earth causing seasons

Hemisphere	Season	Diagram	Angle of rays	Length of day/night
March			**March**	
Northern	Spring		The same angle of rays and length of day/night everywhere on Earth	
Southern	Autumn			
June			**June**	
Northern	Summer		North warm because:	
			Sun high in the sky	Long days to receive Sun
Southern	Winter		South cool because:	
			Sun low in the sky	Long nights to lose heat
September			**September**	
Northern	Autumn		The same angle of rays and length of day/night everywhere on Earth	
Southern	Spring			
December			**December**	
Northern	Winter		North cool because:	
			Sun low in the sky	Long nights to lose heat
Southern	Summer		South warm because:	
			Sun high in the sky	Long days to receive Sun

There is not much seasonal change near the Equator, since the Sun always appears high in the sky; it therefore stays warm all year. Seasonal variations are moderated by nearby bodies of water in the same way as daily temperatures. So, coastal areas normally remain cooler in summer than inland areas, but are warmer in winter.

2.3.3 The phases of the Moon

Like the Earth, half the Moon is lit by the Sun and half is always in darkness. The Moon takes about 27 days to go around, or orbit, the Earth. When the half of the Moon that is lit by the Sun faces the Earth, we can see the whole Moon – this is called the full Moon. As the Moon continues its orbit, we see less and less of the lit side and more and more of the dark side. After around 13 days, the dark side of the Moon is facing us, so we cannot see it at all – this is the new Moon phase. After that, we see more and more of the lit side of the Moon as it orbits back towards full Moon phase again, as in Figures 2.4. and 2.5.

Figure 2.4. The phases of the Moon

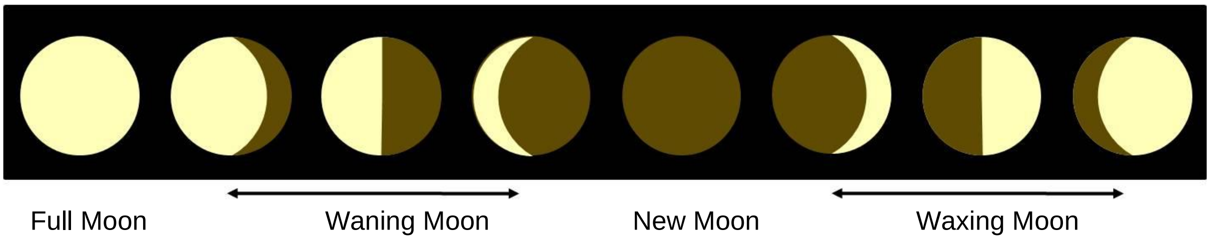


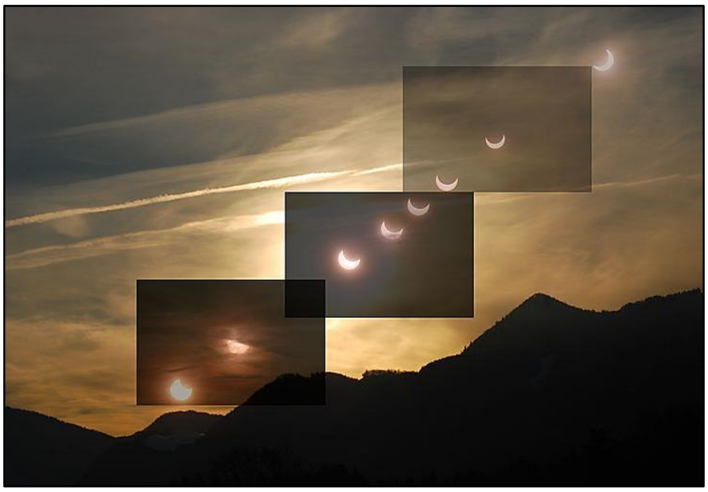
Figure 2.5. The Moon becoming full – a collage of three photographs

2.3.4 Eclipses

The orbit of the Moon is at an angle to the orbit of the Earth, so usually the Moon does not move between the Earth and the Sun and the Earth does not move between the Moon and the Sun.

Sometimes however, the Moon does move between the Earth and the Sun; this is seen as a **solar eclipse** on the Earth. Although the Moon is much smaller than the Sun, it is much nearer the Earth, so when it is in between, it can completely cover the Sun. During such a solar eclipse, the Moon is seen to cover the Sun only from some parts of the Earth; in other areas, a partial eclipse is seen, as in Figure 2.6.

Figure 2.6. A collage of photographs of a partial solar eclipse, seen from Germany



If you want to watch a solar eclipse, you must protect your eyes, by wearing special eclipse glasses. As you watch, you will see the shape of the Moon as it gradually covers the Sun, while the Earth becomes darker and darker. Then the Moon moves on and normal daylight slowly reappears.

When the Moon moves behind the Earth, and the Sun, Earth and Moon are in a line, the shadow of the Earth covers the Moon in a **lunar eclipse**. Earth's shadow moves across until it covers the whole Moon and the Moon can no longer be seen. Then the shadow moves on and the Moon appears again. As this happens, refraction of light by the Earth's atmosphere may colour the Moon reddish-orange for a time, Figure 2.7.

Figure 2.7. A photo collage of a lunar eclipse

3 Earth is a system which has changed over time

3.1 Geological time span

The Earth, as measured by **radiometric dating**, is the same age as the solar system, 4.6 billion years old (4600 million years old).

Before radiometric dating became available, several geologists had tried to estimate its age. They had concluded that it was very old indeed and had written that studying the Earth was like looking into an '*abyss of time'* (John Playfair in 1805) with '*no vestige of a beginning – no prospect of an end*' (James Hutton in 1795). Although, at that time, it was not possible to discover the age in years (or millions of years) of any Earth event, it was possible to put geological events in order. Ordering events is called **relative dating**, since it allows us to say which event was older and which younger, relative to one another.

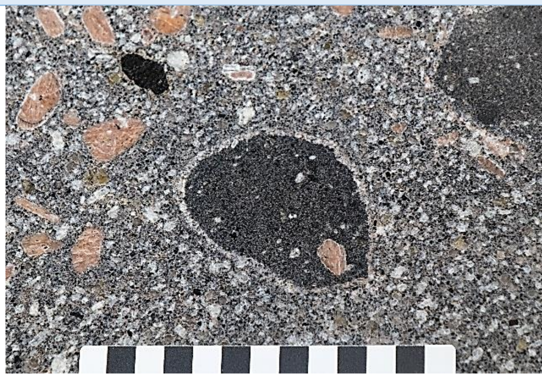
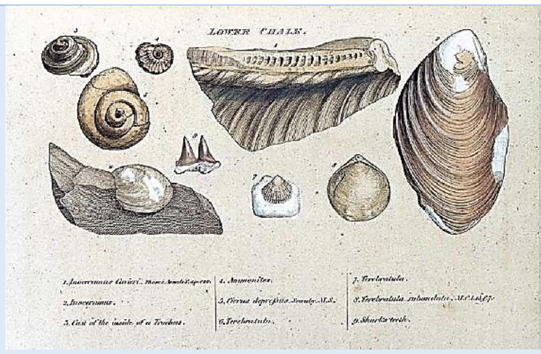
3.2 Relative dating

Several different methods are used in **relative dating**. These were discovered long ago and have been used by geologists ever since. They are shown in Table 3.1. Some of the methods are <u>principles</u> because they work most of the time, but there could be particular geological circumstances where they do not apply; others are <u>laws</u>, which always work, so long as observations are made carefully.

Table 3.1. Relative dating methods

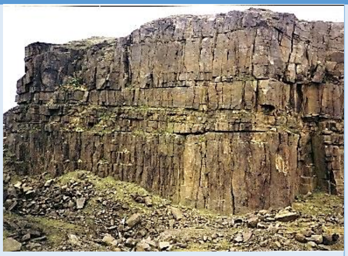
Relative dating method	First described by:	Details of method	Example
Principle of superposition of strata	Nicholas Steno in 1669	When rocks are laid down, those on top are the youngest (exceptions are, for example, when a sequence is overturned by deformation or when faulting has pushed an older sequence over a younger one)	 Layers laid down in a glacial lake called varves, Barmston, North Yorkshire – youngest on top  Overturned fold, The Lizard, Cornwall – the lower part of the fold is overturned, with older rock on top

Table 3.1. Relative dating methods, continued

Relative dating method	First described by:	Details of method	Example
Law of cross-cutting relationships	Nicholas Steno in 1669	Anything (e.g. fracture, rock, vein, erosion surface) that cuts across anything else must be younger	 Cross-cutting white mineral veins, Porthmeor, Cornwall. The top right-bottom left vein cuts the top left-bottom right one and so is younger; both cut the older bedrock
Law of included fragments	Charles Lyell in 1830	Any fragment included in another rock must be older	 Shap granite including dark rock fragments, Shap, Cumbria
Law of faunal succession	William Smith in 1816	Groups of fossils follow one another in a known order in the rock sequence, allowing us to put the rocks in order of time	 Drawings from William Smith's book of a group of fossils used to date a rock, Lower Chalk in England
Deformed/ metamorphosed rocks must be older than those with none – a law	No known person	Since deformation and regional metamorphic events affect all rocks in a region, any un-deformed or non-metamorphosed rocks must be younger	 Unconformity in Vallis Vale, Somerset. The upper rock is younger than the deformed and tilted rock beneath

Some of these relative dating methods are based on two other important principles, first described by Nicholas Steno, as shown in Table 3.2.

Table 3.2. Principles of the laying down of sediments, lavas and volcanic ash

Rock formation principle	First described by	Details	Example – following the principle	Example – not following the principle
Principle of original horizontality	Nicholas Steno in 1669	Sediment layers are originally laid down horizontally (as are lavas and volcanic ash) – but sometimes they are laid down at an angle	 Carboniferous sandstones laid down horizontally – Crowden Quarry, Derbyshire	 Carboniferous sediments not originally laid down horizontally – cross-bedded sands, Walkley Bank, Sheffield, Yorkshire
Principle of lateral continuity	Nicholas Steno in 1669	Sedimentary layers continue laterally over large areas (as do lava and ash deposits) – but there are unusual situations where this is not so	 Laterally continuous Carboniferous sedimentary rocks, Mam Tor, Derbyshire	 Buried valley, Bardon Hill Quarry, Leicestershire - the sediment layers stop at the valley sides

These principles and laws can be used to work out the geological history of an area, without knowing the actual age of the rocks.

Box 3.1. Using relative dating methods to work out the geological history of the rocks; in this rock sequence in the Negev Desert in Israel:

- The horizontal sedimentary rocks were deposited in sequence so, according to the 'Principle of superposition', the oldest rocks are at the bottom
- The rocks were originally laid down horizontally and continuously over a broad area, as in the 'Principle of original horizontality' and the 'Principle of lateral continuity'
- The thicker layer near the base of the sequence is a conglomerate containing pebbles; according to the 'Law of included fragments' the pebbles must be older than the layer in which they are found.
- The rocks have been cut by a vertical dyke of igneous rock which, according to the 'Law of cross-cutting relationships', must be younger than the horizontal sediments it cuts
- Everything has been cut by the erosion surface that is today's cliff face, so this is the latest event, according to the 'Law of cross-cutting relationships'

Box 3.1. Using relative dating methods to work out the geological history of the rocks, continued

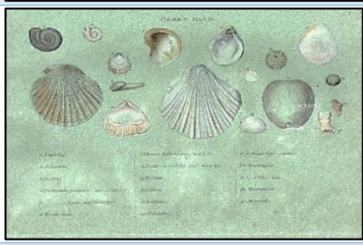
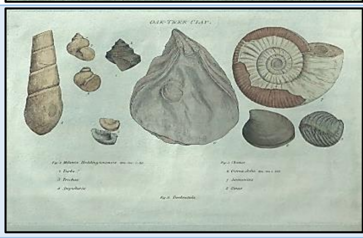
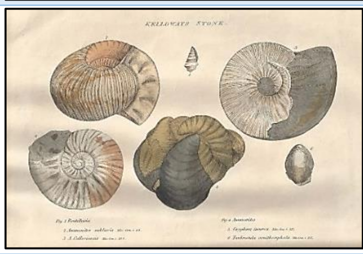
So the history of the rocks is:

Latest event -
* the modern cliff top and face was eroded
* the rock sequence was cut by a sheet of liquid magma that solidified into a dyke
* the remaining layers were laid down, becoming younger upwards
* the lowest bed in the cliff face was deposited, followed by the
* conglomerate containing the pebbles

Earliest event -
* a rock was formed that was later eroded to form pebbles

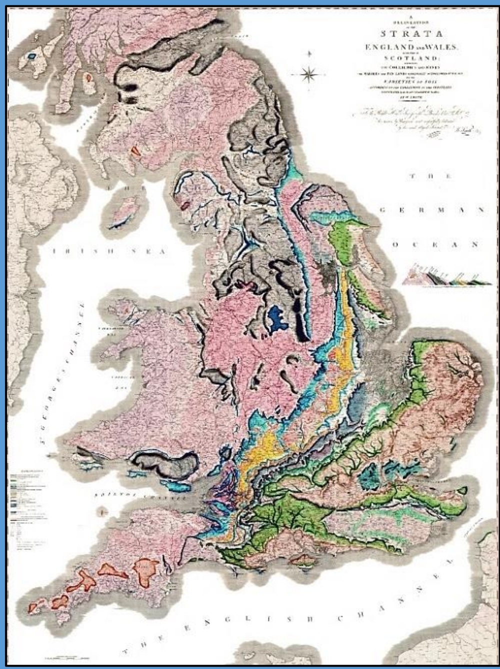
William Smith used fossils to work out the relative dating of rocks, describing his method as the ‘Law of faunal succession’. He recognised that many sedimentary rock layers contained certain groups of fossils and these could be traced over large areas. This meant that wherever he found a rock with a certain group of fossils, he knew it was a rock of the same age. This method is called **correlation**. He also realised that layers containing certain groups of fossils were always found in the same order. This meant that when he found a rock with one group of fossils, he knew that rocks with other groups of fossils would always be found above or below, as shown in Table 3.3. Although Smith used his method to correlate rocks and place them into sequences, he did not know why the fossils were always found in the same order. It was only later that Charles Darwin realised that the reason for this order was **evolution**.

Table 3.3. William Smith’s method applying the ‘Law of faunal succession’, based on fossils he collected across England.

William Smith’s sequence		Age related to periods of the geological time scale, recognised after Smith	Drawings of William Smith's original fossil groups
Youngest	Lower Chalk	Late Cretaceous age	
	Green Sand	Early Cretaceous age	
	Oak Tree Clay (now called Kimmeridge Clay)	Late Jurassic, Kimmeridgian age	
Oldest	Kelloways Stone	Middle Jurassic age	

Box 3.1E. William Smith – the 'Father of English Geology'


William Smith



Smith's geological map of the UK, 1815

William 'Strata' Smith was born in 1769 into a poor family in Oxfordshire. He had a very basic education and trained as a surveyor when he was 18. Later, when he was surveying a coalmine in Somerset, he noticed that the rocks were in layers, that they all tilted (dipped) in one direction and that they contained particular fossils. If a coal seam occurred under a layer with a certain type of fossil, when that layer was found elsewhere, the chances were high that a coal seam was under it too. Predicting where coal seams could be found was valuable information, especially in the late 1700s, when the Industrial Revolution was beginning in the UK and coal mining was becoming vital.

Later when he was surveying land to excavate the Somerset Coal Canal, he noticed once again that fossils only occurred in particular layers and that those layers could be identified by their included fossils. This led in 1794 to his writing 'The principle of faunal succession' – that strata can be correlated from one place to another based on the fossils they contained. Eventually, in 1799, this idea led Smith to produce the first geological map of the city of Bath area. The colours he used for the various geological sequences or strata on this map, are much the same as those used for geological maps today.

During the next 15 years, Smith took a series of engineering jobs, travelled tens of thousands of miles and surveyed 50,000 square miles of land, all travelling in a springless horse-drawn carriage and staying in wayside coaching inns. By 1815 all this effort led him to produce the first geological map of the UK, an extraordinary success for a relatively uneducated man of low social status.

It is even more astonishing when it is remembered that Smith had no idea about geological time. He did not know that, in most instances, the lower rocks are older than those on top. He had no idea that the changes he observed in the fossils through the layers were evolutionary changes. He referred to a 'wonderful order', meaning the order created by God. At the time, most people believed that the Earth had been formed by God over six days, about 6000 years before.

When his map was first published, William Smith was overlooked by the scientific community; his relatively humble education and social standing prevented him from mixing easily with learned scientists. He became bankrupt and was sent to prison. It was only late in his life that he received recognition for his achievements and became known as the 'Father of English Geology'. In 1832, aged 63, he was awarded the first Wollaston Medal (the 'Oscar' of the world of rocks) by the Geological Society of London, which had dismissed him previously.

Elizabeth Devon

We can now apply Smith's method more widely, since we know that certain fossils are only found in certain ages of rocks. Thus, by recognising the fossils, we know the geological age of the rocks, as in Table 3.4.

Table 3.4. Typical fossils found in rocks of different ages

Geological age of rock	Fossil found only in rocks of this age	Fossil image
Quaternary	*Argopecten gibbous* scallop shell – lives on the sea bed but can clap its shells to move and escape from predators; found in Neogene, Quaternary and modern sediments; this is a modern specimen	
Neogene	Gastropod from the Red Crag, East Anglia	
Paleogene	Shark tooth from Abbey Wood, London	
Cretaceous	*Micraster* echinoderm, a sea urchin living on and within the sea floor sediment; this species is found only in the Cretaceous although other *Micraster* forms are found in the Paleogene. This specimen is from the North Downs in south east England	

Table 3.4. Typical fossils found in rocks of different ages, continued

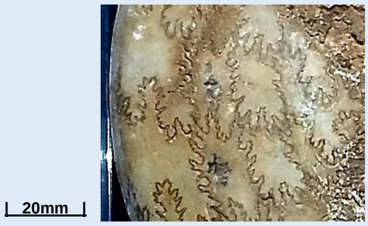
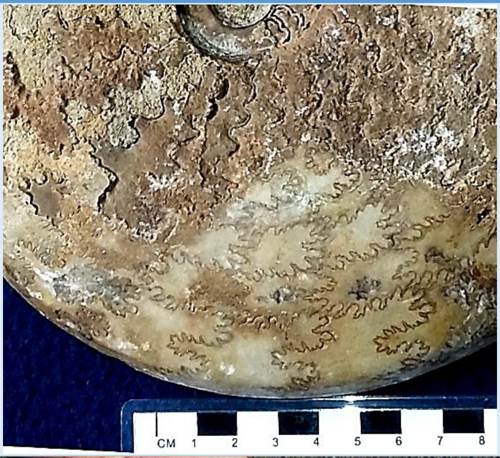
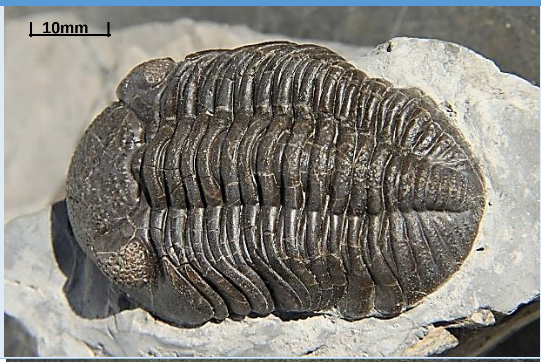
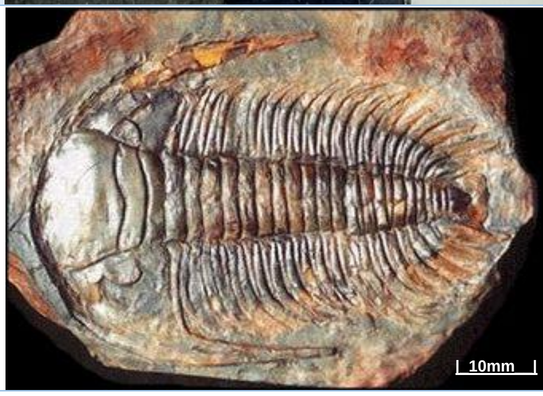
Geological age of rock	Fossil found only in rocks of this age	Fossil image
Jurassic	An ammonite which lived like an octopus with a shell, swimming in the sea; the walls between the chambers had very complex shapes, only found in Jurassic and Cretaceous ammonites. This specimen is from Horn Park Quarry, Beaminster, Dorset 	
Triassic	*Ceratites* ceratite ammonoid; this lived swimming in the sea like an octopus with a shell; had walls between chambers that were smoothly curved towards the mouth of the shell, but complex in the other direction; this specimen from Oberer Muschelkalk. Hohenlohe, Germany. Ceratites are not found in England 	
Permian	Goniatite ammonoid (also found in Carboniferous and late Devonian rocks); like a small octopus with a shell; lived swimming in the ocean – had walls between chambers with simple zig-zag shapes 	
Carboniferous	Solitary rugose corals which lived rooted in the sea floor. This specimen is from the Peak District in Derbyshire.	

Table 3.4. Typical fossils found in rocks of different ages, continued

Geological age of rock	Fossil found only in rocks of this age	Fossil image
Devonian	*Phacops* trilobite – lived on the sea floor, probably as an active predator; this specimen is from the middle Devonian Silica Shale, Ohio, USA	
Silurian	Three *Monograptus* graptolites, each with a single arm or stipe carrying a colony of graptolite animals; floated in the ocean. This example is from Wales.	
Ordovician	*Didymograptus* graptolite with two arms or stipes. Each of the arms carried a colony of small graptolite animals; the colony floated in the ocean. Specimen from South Wales	
Cambrian	*Paradoxides* trilobite; these lived on the sea floor and were probably predators	

Box 3.2E. The Chronicles of Charnia

In 1956, when Tina Batty was fifteen, she visited a rock exposure in Charnwood Forest near her home in Leicestershire. She found a fern-like fossil. She knew the rocks were Precambrian in age and next day, she told her geography teacher about the find. Her teacher replied 'There are no fossils in Precambrian rocks' and dismissed the idea completely. Later Tina went back and made a pencil rubbing of the fossil. Then when she returned the following year, the fossil had been removed!

What had happened is that group of fifteen-year old schoolboys had gone to the same place and found the same fossil. One of them, Roger Mason, also took a rubbing of the fossil and showed it to his father, who taught at the local university. He showed the rubbing to Trevor Ford, a young geology lecturer, who was really puzzled. He knew that the rocks were Precambrian and so should not contain fossils. Nevertheless, he did visit the exposure later, and saw not only that fossil but strange ring shapes as well. Ford had the fossil removed to the nearby museum and wrote a scientific paper for the regional journal, the *Proceedings of the Yorkshire Geological Society*. This was the first ever scientific account of a Precambrian fossil.

Although Tina wanted to study geology at school she was not allowed to. But Roger did go on to study geology and became a geology professor. In the 1970s Tina spotted her fossil on a children's TV programme with its 'finder' Roger Mason. She sent Mason an email with a poem she had written about Charnia and her own story. Eventually, at the 50th anniversary of the Charnia find, in 2007, Tina was invited to the celebration. She cut the 'Charnia cake' with Roger Mason and Trevor Ford, as the anniversary speaker announced that Charnia is 'probably one of the most important fossils ever found'.

Since then many more Precambrian fossils have been found and we now know that Charnia and the ring markings are part of a large assemblage of fossils from that time, around 560 million years ago. We also know that the fossils must have been seen even earlier, because the rock exposure is part of a quarry that the quarrymen called 'the ring quarry'.

Charnia masoni in Leicester Museum – 15 cm long

What Charnia may have looked like when alive

This box is named after the famous children's book series, 'The Chronicles of Narnia'.

Chris King

When geologists were using fossils to correlate and sequence rocks, they discovered that there were sudden changes in groups of fossils at certain places in the fossil record. We now know that this was because there were big extinction events at those times, but the early geologists were most interested in how these changes could be used to divide up rocks. The fossils were used to identify geological periods (with the names shown in the first column of Table 3.4).

Box 3.2. An example of a geological period – the Triassic

The Triassic period is the first period of the Mesozoic ('middle life') Era and was named by Freidrich von Alberti in 1834 because of its three major layers (*tri* = three), which are found throughout Germany and across northwest Europe. These are red beds at the bottom, followed by a limestone, with a mudstone/sandstone series on top. He was able to distinguish the Triassic rocks from under- and over-lying rocks because of the major changes in fossils found at the base and the top of the sequence. We now know that these were the results of large-scale mass-extinction events.

Nowadays, wherever possible, the positions of major boundaries in the geological column are identified by a 'Global Boundary Stratotype Section and Point' (GSSP). A place somewhere on Earth is found where there is a series of fossiliferous beds of the correct age, where the exact position of the boundary can be found. A 'golden spike' is placed at that point to mark this important reference point.

The 'golden spike' for the bottom of the Triassic (and therefore the top of the preceding Permian period) is at Meishan in the Zhejiang Province of China, where a conodont microfossil called Hindeodus parvus first appears in the geological sequence.

The top of the Triassic (and so the base of the Jurassic period) has its 'golden spike' at Kuhjoch in the Tyrol of Austria, where the ammonite Psiloceras spelae tirolicum is first found.

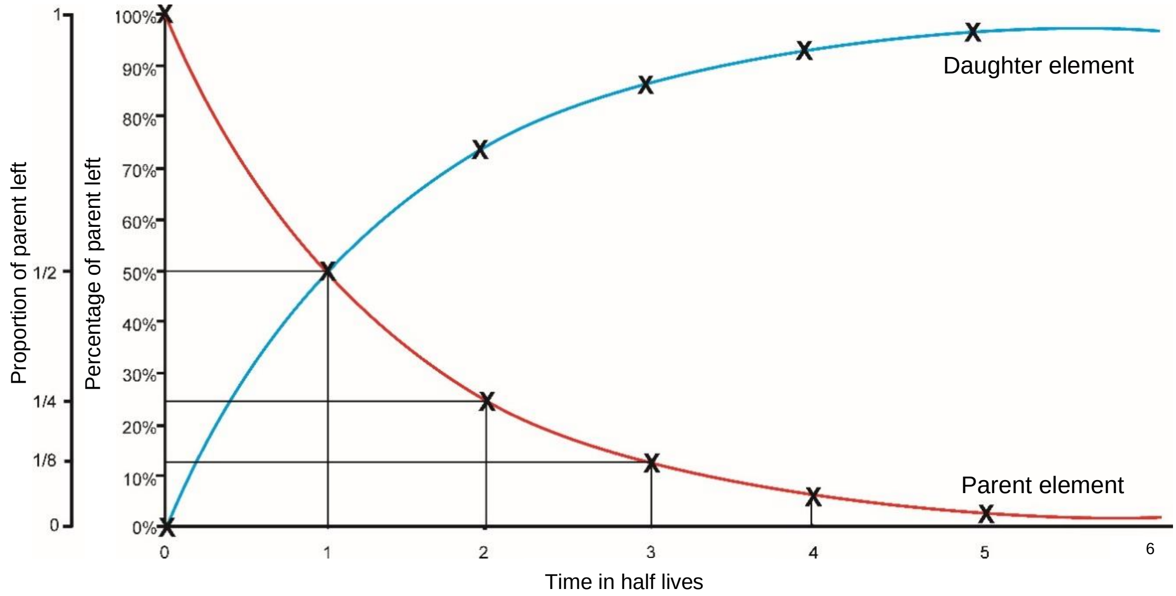
The 'golden spike' bronze marker at one of the geological boundaries within the Triassic Period – with a plaster cast of the ceratite, which first appears in the geological record there, marking the boundary

Relative dating methods had been used to work out the relative ages of rocks and geological periods for many years, but we did not know how old the periods were, or the ages of the boundaries between the periods, until radiometric dating became available.

3.3 Absolute dating

Radiometric dating became possible when it was discovered that the radioactive elements contained by some rocks and minerals break down to form other elements. Their decay over time happens in a predictable way that can be shown on a graph; this is often called the **radioactive decay curve** (Figure 3.1).

Figure 3.1. The radioactive decay curve for the breakdown of all radioactive materials



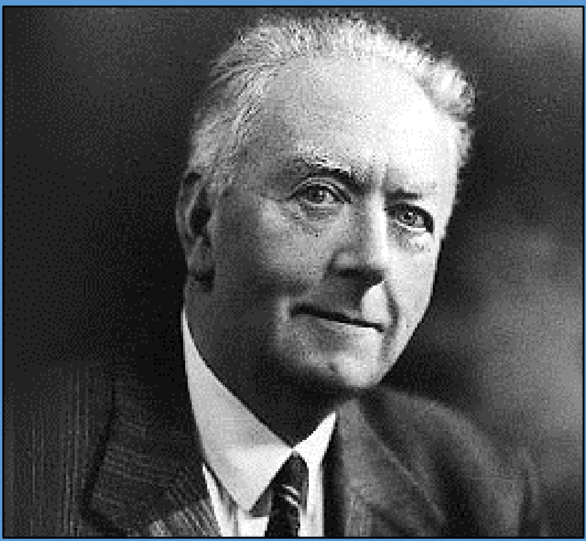
The radioactive element that decays is called the parent; the new element produced by the decay is the daughter. The graph shows that after a certain time, half the element has broken down to produce the daughter; this time is called the **half-life**. After another half-life, another half of the parent has broken down, so there is only a quarter left; the substance then contains 25% of the parent and 75% of the daughter. After a third half-life time has passed by, another eighth (12.5%) of the parent has broken down, so the substance is 12.5% parent and 87.5% daughter. Breakdown continues, with the percentage of parent becoming less and less as the amount of daughter becomes greater and greater.

Although all radioactive materials break down according to this pattern, the lengths of their half-lives vary enormously, from billions of years to microseconds and less. If we choose a radioactive element with a known rate of breakdown, we can measure the amounts of parent and daughter products, to give us the age when the element first formed. This then gives the age of the mineral or rock in which it is found. This method is called **absolute dating** because it gives an age in years, thousands, millions or billions of years. As the measurements involve a calculated small amount of error, radiometric dating measurements are always given with the potential error shown.

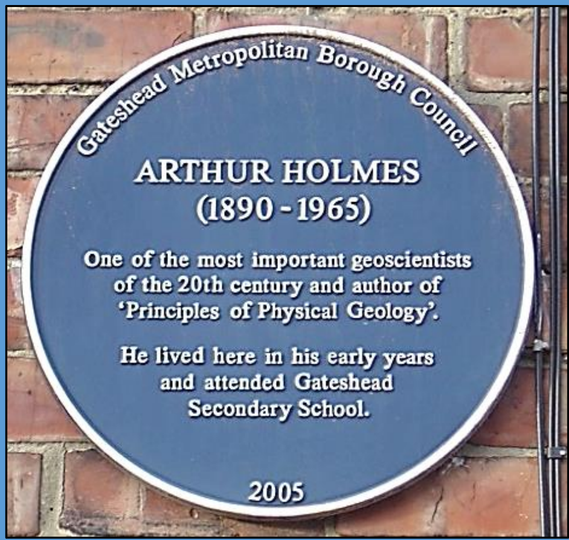
Box 3.3. The error range given with radiometric absolute dates.

The city of Edinburgh in Scotland is built around an ancient volcano. Feldspar minerals from the volcanic rocks were used to date the eruption. The date given by the radioactive decay of the argon in the feldspar was 349 $\pm$ 4 million years, showing that the volcano erupted in Carboniferous times between 353 and 345 million years ago.

Box 3.3E. Arthur Holmes – radioactive dating and a mechanism for plate tectonics



Arthur Holmes



Blue plaque on the home of Holmes

Arthur Holmes was encouraged to take up geology by an inspirational schoolteacher, like many other people before him and since. It was Mr. McIntosh at Gateshead Secondary School, who introduced him to the works of the physicist Lord Kelvin and the Swiss geologist Edward Suess. This work influenced his research at Imperial College in London as well.

Holmes was born in County Durham in 1890 and during his career until 1965, he made two major breakthroughs in the way we study and understand Earth processes. Using the newly discovered technique of radioactive dating, he was able to make much more realistic estimations of the true age of the Earth than had been possible before then. Then, in 1913 for the first time, he was able to put absolute dates to the relative geological time scale – dates he refined in later years as the technique improved.

Holmes was also one of the first geologists to follow the evidence put forward by Alfred Wegener in support of his theory of Continental Drift. Long before the plate tectonic revolution of the 1960s, it was Holmes who 'speculatively' suggested a mechanism for the movement of the continents – by convection currents in the underlying mantle. His idea was presented to the Geological Society of Glasgow in 1928 and appeared in several editions of his popular book 'Principles of Physical Geology', published in 1944 when he was Head of the Geology Department at Durham University. This book became a standard textbook for many future geology students, and like his own teacher, Arthur Holmes inspired many more.

Pete Loader

Absolute dating can only be used for rocks or minerals which contain the right type of radioactive elements and gives the date when that rock first formed. This works well for most igneous and some metamorphic rocks. It is not so useful for sedimentary rocks, since the grains of sediment were formed earlier, before being eroded and deposited. This makes it difficult to link radiometric dates with fossil correlation dates, as the fossils are found in the sedimentary rocks. This is one of the reasons why it took a long time to allocate absolute dates to the boundaries between the periods in the geological column. However, these dates have nearly all now been confirmed, allowing us to produce the geological column with dates, shown in Table 3.5. Major events in geological history have been added to the final column of this table.

Table 3.5. The main subdivisions of geological time based on the latest International Chronostratigraphic Chart published by the International Commission on Stratigraphy*

Eon	Era	Period	Abbre-viation	Age (Millions of years ago (Ma))	Major events
Phanerozoic	Cenozoic	Quaternary	Q	0 2.6	3.3 Oldest stone tools
		Neogene	N	23	
		Paleogene	Pg	66	50 Himalayan mountains 66 K-Pg mass extinction
	Mesozoic	Cretaceous	K	145	130 Early flowering plants
		Jurassic	J	201	160 Early birds 190 Opening of Atlantic Ocean
		Triassic	T	252	220 Early mammals 252 'Great dying' mass extinction
	Palaeozoic	Permian	P	299	299 Supercontinent Pangaea first formed
		Carboniferous	C	359	315 Early reptiles
		Devonian	D	419	370 Early amphibians
		Silurian	S	444	
		Ordovician	O	485	400 Early insects 430 Early land plants
		Cambrian	Cm	541	530 Early fish 541 Life with shells/hard parts
Precambrian	Proterozoic			2,500	2,000 Early multicelled organisms 2,100 Early eukaryotes
	Archaean			4,000	2,700 Free oxygen in atmosphere 3,500 Early bacteria and algae
	Hadean			4,600	4,000 Oldest known rocks 4,600 Origin of the Earth

* As rock-dating methods improved, some of the dates in the table have changed over time. Table 3.5 shows the latest version.

Box 3.3E. Geological period namers

Permian

The Permian was named by Roderick Murchison in 1841 following a field trip surveying rock formations in the area between Moscow and the city of Perm in Russia. Murchison was born in Scotland and lived mainly in London

Carboniferous

The Carboniferous was named by William Conybeare in 1822 in an early geology textbook he wrote with William Phillips. The word means ‘coal-bearing’ based on the Latin words *carbo* (coal) and *fero* (I carry). Conybeare (left) was born in London and later became Dean of Llandaff Cathedral near Cardiff in South Wales. Phillips (right) was also born in London and co-founded the Geological Society of London (the first such society in the world)

Devonian

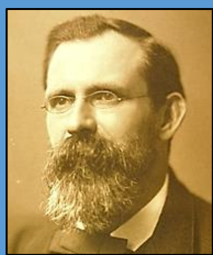
The Devonian was named after the county of Devon in 1839, following a long debate between Henry de la Beche and George Greenough on one side and Roderick Murchison and Adam Sedgwick on the other. The argument was won by Sedgwick (left) and Murchison (right)

Silurian

The Silurian was named by Roderick Murchison in 1835 after an ancient Welsh tribe, the Silures. Murchison began his mapping of the Silurian rock in South Wales. He was born in Scotland but lived mainly in London. He became known as ‘The King of Siluria’ and later became director of the Geological Survey

Ordovician

The Ordovician was named by Charles Lapworth after an ancient Welsh tribe, the Ordovices. Earlier, in the late 1830s, Sedgwick and Murchison had mapped the same rocks, Murchison claimed them as Silurian and Sedgwick as Cambrian. This caused a furious argument that was only later resolved by Lapworth (after both Murchison and Sedgwick had died). Lapworth was born in Oxfordshire, worked mainly in Scotland and Shropshire, and lived in Birmingham, where a museum is named after him



Cambrian

The Cambrian was named by Adam Sedgwick in 1835 based on *Cambria*, the Latin name for Wales. Sedgwick was born in Yorkshire and worked in Cambridge; he introduced Charles Darwin to geology. Sedgwick’s mapping of Cambrian rocks began in North Wales. A museum in Cambridge is named after him

Chris King and Duncan Hawley

3.4 Rates of processes

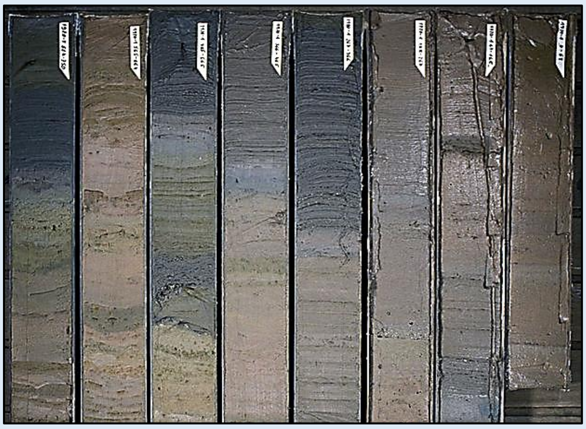
At one time, it was thought that most geological processes happened slowly and steadily. We now know that, whilst some are indeed very slow and steady, others can be very fast and catastrophic. For example, it takes millions of years for a sedimentary rock sequence to be laid down, but individual layers can be deposited in seconds. Similarly, the cooling of liquid magma deep underground until it becomes a solid igneous rock can take millions of years, whilst volcanoes can erupt in seconds. Rocks can be uplifted slowly, as when the overlying ice has melted allowing the land to rise, or can be raised suddenly, in earthquakes.

It now seems that evolution, which had also been thought of as a steady process, often happens in sudden bursts, whilst mass extinctions also often seem to be sudden catastrophes.

So it has become clear that the four billion year-long geological record is a record of a combination of extremely slow processes interspersed by violent catastrophic ones, with other processes acting at all time-spans in between.

Box 3.4. From very, very fast, to very, very slow processes

In the deep sea, fine muds settle out of suspension in sea water very, very slowly, so that it can take millions of years to build up a sediment sequence. However, sometimes on land, in coastal areas and in ocean depths, layers of sediment can be laid down very much more quickly, in days or even hours, by storms, landslides or other catastrophic events.



Cores of deep sea sediments from the deep sea near Greenland; the sediment layers have built up over long time-spans

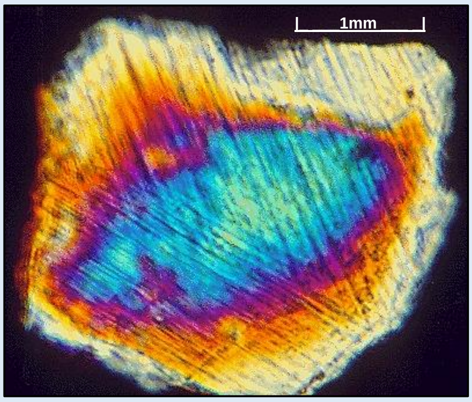
Grey layer of an 8,000-year-old tsunami deposit in Scotland, laid down in minutes, with layers of dark peat above and below

Box 3.5. Catastrophic impact events

Objects from space often collide with the Earth and other planets, but most of these are very small and are not detected. However, asteroids of 1 km diameter hit the Earth every half million years on average, whilst 5 km diameter asteroids collide with the Earth every 20 million years or so. Many small asteroids break up in the atmosphere, but larger ones hit the Earth and produce craters. The size of the impact depends upon the diameter, density, speed and angle of the colliding body. Although volcanic craters can often look very similar to impact craters, only impact craters have small glassy beads called tektites and 'shocked quartz', produced by deformation of the quartz during the impact. Some impacts produce iridium layers too, as well as layers of soot and ash.

Box 3.5. Catastrophic impact events, continued

Common tektite shapes – dumbbell and teardrop

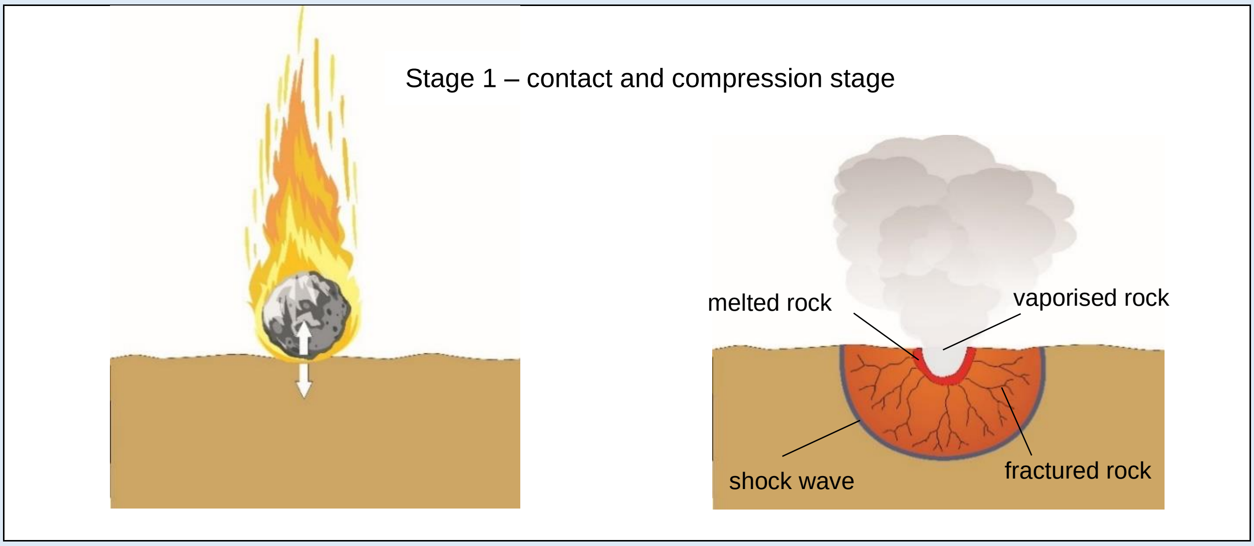


Shocked quartz with deformation planes seen under the microscope in cross-polarised light

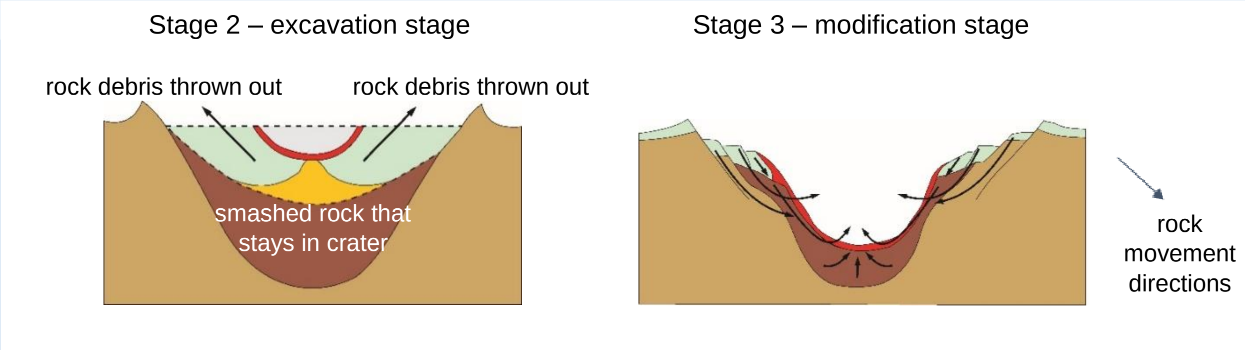
Lonar crater in India – produced by an impact thought to have been about 52,000 years ago

The 100 km-wide Manicouagan Crater in the Côte-Nord region, Québec, Canada, seen from the International Space station – formed by a 215Ma impact

The geology of impacts is unusual because many of the events happen in seconds, rather than the much longer time-spans usually studied by geologists. Impacts usually have the stages shown below. The result is the familiar crater shape, shown by Meteor Crater, Arizona, U.S.A.



Box 3.5. Catastrophic impact events, continued



Meteor (Barringer) Crater near Flagstaff in Arizona, USA, showing a typical impact depression with a raised centre, surrounded by the high crater rim – formed around 50,000 years ago

4 Earth's system comprises interacting spheres

The whole Earth system is formed of many, many sub-systems. These can be divided into those of the geosphere, hydrosphere, atmosphere and biosphere, although there are many interactions and feedbacks between these different sub-systems, as shown in Chapter 1.

4.1 Geosphere

The **geosphere** is the solid Earth. It includes the whole Earth, with its core, mantle, crust, rocks, minerals, fossils and soils. It also includes all the processes that affect the solid Earth and its materials.

4.1.1 Earth materials and properties

The outer part of the Earth is formed of rocks and these in turn are formed of minerals or fragments of other rocks and are often overlain by soil.

4.1.1.1 Minerals

Minerals are naturally formed non-organic substances with fixed crystal structures and properties. They can be made of single elements, but most are chemical compounds of two or more elements. Because naturally formed substances are usually not as pure as manufactured chemicals, they may have small differences in chemistry, crystal structure and physical properties. Different minerals can be recognised by their properties – key properties are colour, crystal shape, hardness and the way they break. Some minerals have particular properties that aid their identification, such as the reaction of calcite with dilute hydrochloric acid, the salty taste of halite, or the high density and metallic shine of ore minerals like galena. Common minerals are shown in Table 4.1.

Table 4.1. Common minerals, their chemistry, shape and physical properties

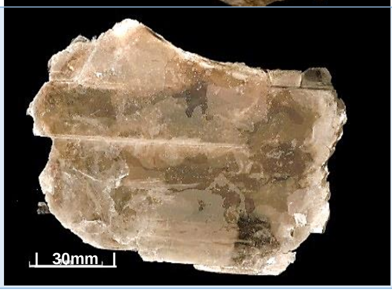
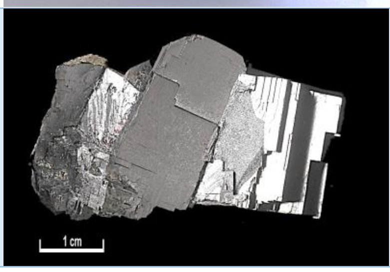
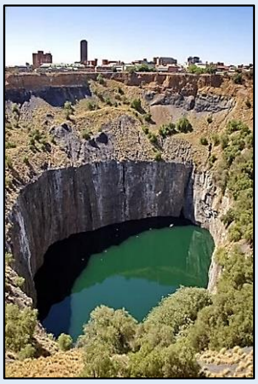
Name	Image	Chemistry	Shape of good crystals	Physical properties
Quartz Large quartz crystals with pyrite from: Cornwall		Silicon dioxide; SiO_2	Near hexagonal (6-sided) shapes	Usually white, grey or colourless, but may have other pale colours; hard; difficult to break
Feldspar Crystal from: the Roneval veins, Lewis, Outer Hebrides, Scotland		Calcium/ sodium/ potassium silicate; range from $CaAl_2Si_2O_8$ to $(K,Na)AlSi_3O_8$	Often box-shaped	Usually white or grey, sometimes pink; hard; breaks along flat surfaces
Mica Crystal from: Loch Nevis Mica Prospect, Knoydart, Inverness Scotland		Complex silicate of silicon and oxygen with calcium, sodium, potassium, aluminium, magnesium and/or iron	Near hexagonal (6-sided) plates	Usually colourless or black; low hardness; easily breaks into flat sheets

Table 4.1. Common minerals, their chemistry, shape and physical properties, continued

Name	Image	Chemistry	Shape of good crystals	Physical properties
Calcite Crystals from: Egremont, Cumbria		Calcium carbonate; $CaCO_3$	Dog-tooth spar is a common form, shaped like dogs' teeth	White or colourless; fairly low hardness; easily breaks into squashed cube shapes; reacts with dilute hydrochloric acid
Halite Crystals from: Winsford Rock Salt Mine, Cheshire		Sodium chloride; NaCl	Cube-shaped	Colourless, white or pink; low hardness; very easily breaks into cube shapes; salty taste
Gypsum Crystal from: Jurassic clay near Weymouth, Dorset		Calcium sulfate; $CaSO_4.2H_2O$	Thin crystals. Sometimes forms 'desert roses'.	Colourless, white or pink; low hardness; easily breaks along flat surfaces
Pyrite Crystals from: West Wheal Kitty, St. Agnes, Cornwall		Iron sulfide; FeS_2	Often cube-shaped	Shiny, brassy yellow; hard; difficult to break; high density
Galena Crystals from: Wanlockhead Lead Mine, Dumfries, Scotland		Lead sulfide; PbS An ore of lead	Often cube shaped	Shiny grey; low hardness; easily breaks into cube-shapes; high density

Box 4.1. An unusual mineral – diamond

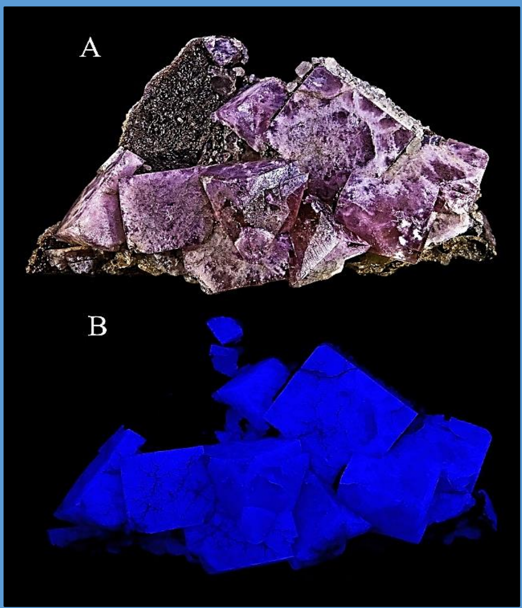


Diamonds are formed under great pressure deep beneath the Earth's surface from the element carbon. They are brought to the surface in unusual volcanic rocks called kimberlites. The rising magma drills circular pipes upwards through the crust at great speed, carrying the diamonds. Diamonds are mined from kimberlite pipes, like the 'Big Hole' in Kimberley, South Africa, shown in the photo. When kimberlites are eroded, the diamonds are transported by rivers and deposited in alluvial deposits; many diamonds are mined from these deposits as well.

Diamonds are so special because strong atomic carbon bonds make them the hardest mineral on Earth. They also have a very bright shiny surface. Rough diamonds, like the one shown in the central photo can be cut to make them reflect the light even more, making them the most valuable gemstones, widely used in jewellery. Smaller diamonds are used for industrial cutting and polishing because they are so hard, and are often used in dentists' drills as well.

Box 4.1E. The mineral fluorite

The mineral fluorite (calcium fluoride, CaF_2) is an economically important mineral in England. It is now only mined from the Southern Pennine Orefield in England, although in the past it was mined in the North Pennine Orefield near Durham as well. The fluorite deposits in these orefields formed as hydrothermal vein deposits when hot fluids circulating underground rose through fractures and faults in the rocks, depositing layers of crystals along the walls. This happened at depths of about 3 km during late Carboniferous and early Permian times. The veins contain mainly fluorite with metallic ores like galena (lead ore) and sphalerite (zinc ore). Fluorite is important because it is the only source of the element fluorine (F) in the UK.



Fluorite fluorescing under ultraviolet light. From Boltsburn Mine, Weardale, County Durham.

Box 4.1E. The mineral fluorite, continued

Fluorspar is the commercial term for fluorite and all fluorspar produced in England is of the highest grade, which is used by the chemical industry to make hydrofluoric acid (HF). This acid is used in manufacturing computer chips and for making various chemicals such as fluorocarbons which are used as refrigerants and to make high-insulation plastics. They are also used to make fluoropolymers for the coatings of non-stick pans and for waterproofing textiles.

One special type of fluorite in the UK is Blue John. This rare, semi-precious mineral has attractive purple-blue or yellowish bands of colour and is found only in the Blue John and Treak Cliff Caverns at Castleton in Derbyshire. In the 1800s it was mined because it could be polished to make jewellery or easily carved into small statues and vases. Although mining takes place today, it is now such a scarce mineral that mining is on a small scale.

Blue John bowl, Derbyshire Visitor Centre, Castleton, Derbyshire, originally mined from Treak Cliff Cavern in Derbyshire.

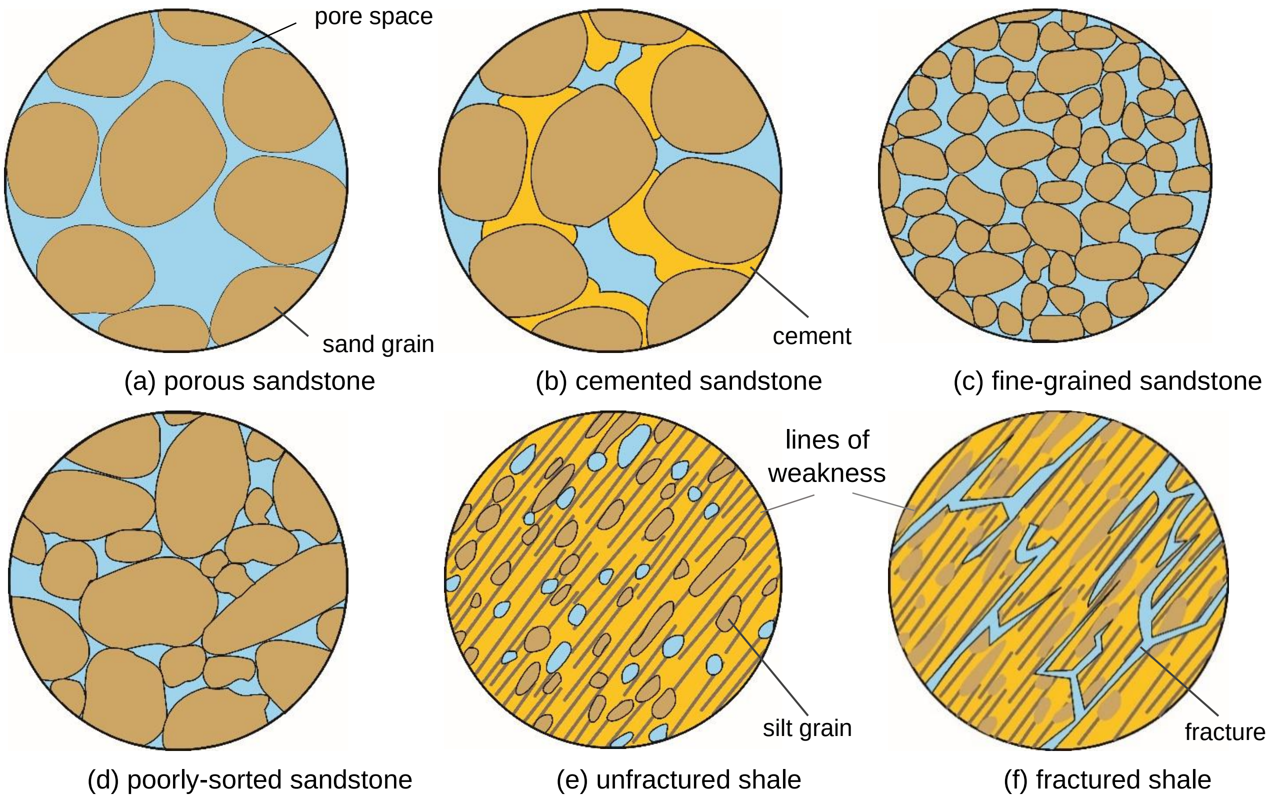
Maggie Williams

4.1.1.2 Rocks

Rocks are naturally formed substances. They are made of minerals, fragments of other rock, or fossils and are formed through the rock cycle processes described in Section 1.4.4. Rocks are identified and described based on their chemical composition and their physical texture. The chemical composition is linked to the minerals that form the rock, while the texture of the rock depends on the types and sizes of particles and how they are arranged. These features link in turn to the resistance of rocks to being worn away, and to their porosity and permeability.

Porosity is the amount of space or pores in a rock, measured as a percentage. 15% porosity is a high porosity for rocks; most rocks have porosities much lower than this. The **permeability** of rock measures how quickly fluids can flow through rocks. Rocks with high porosity have high permeability if the pores are large enough for fluids to flow through and the pores are linked together. Rocks with very small pore spaces, like clays, do not allow fluids to pass through, and are therefore porous but impermeable. Similarly, the gas bubble holes in some lavas are not joined, so the rock again is porous but impermeable (Figure 4.1). Rocks made of interlocking crystals, or which are well cemented or very fine grained, stop fluids flowing through and are **impermeable**, unless they contain cracks and fractures. Porosity and permeability control the amounts of natural fluids such as water, oil and gas that can be stored in and flow through rocks.

Figure 4.1. Porosity and permeability in rocks. The porosity and permeability in (a) has been reduced by cement in (b); permeability in (c) is quite low because the pore spaces are small; permeability in (d) is also low because the pore spaces between larger grains have been filled by smaller ones; the unfractured shale in (e) is impermeable until it is fractured in (f).



Rocks formed of grains that are compressed together and/or naturally cemented together are **sedimentary rocks** – these can have a range of compositions and textures. The most common sedimentary rocks are rich in quartz, feldspar and clay minerals. These can have a range of grain sizes from coarse-grained conglomerates (with rounded grains) and breccias (angular-shaped grains), through medium-grained sandstones to fine-grained sedimentary rocks such as mudstones, shales and clay/claystone. Limestones are also common sedimentary rocks and are formed mainly of fragments of calcium carbonate minerals like calcite, mostly from broken shells. Limestones can be identified because calcium carbonate reacts with dilute acid – a drop of hydrochloric acid on limestone will produce a fizzing reaction. Limestones also range from coarse- to fine-grained and in colour from grey to cream-coloured to the white of fine-grained chalk.

Igneous and metamorphic rocks are formed of interlocking crystals which normally make them very resistant to being worn away and also make them impermeable, unless they are fractured. In coarser examples, the interlocking crystals can be seen by eye or with a hand lens.

Igneous rocks were once molten rock called **magma**, and usually formed as the magma cooled down. As the magma cooled, crystals of minerals grew until they interlocked, as the rock became solid. Minerals of different compositions have different colours and crystallise at different temperatures, so igneous rocks are mixtures of minerals of different colours, shapes and sizes. The crystals normally have random orientations. The only exception to igneous rocks being formed by cooling magma is when magma is blown explosively out of volcanoes as solid blocks or volcanic ash.

Metamorphic rocks are formed from sedimentary, igneous or older metamorphic rocks by **metamorphism** caused by increases in temperature, pressure or both. They form in the solid state, so there is no melting (rocks formed by melting are igneous rocks). The increase in temperature comes either from baking by a nearby magma or from becoming deeply buried. Where pressure is involved, metamorphic rocks can only form in plate-collision situations and not simply by the burial pressure of thick overlying sequences of rock. Metamorphic rocks produced by increased temperature alone have randomly orientated interlocking crystals, whereas metamorphic rocks formed by increased plate-tectonic pressures have interlocking crystals which are orientated at right angles to the pressures. Marble, being a metamorphic rock formed of calcium carbonate crystals, reacts with dilute hydrochloric acid in the same way as limestone.

These properties enable the three great groups of rocks to be distinguished from one another: by studying the grains or crystals, by testing permeability (through dropping water onto the surface or by putting specimens into water and watching for rising bubbles), and by scratching the rocks with a fingernail or a piece of metal, such as a coin. The results are shown in Table 4.2. Limestone and marble also react with dilute hydrochloric acid.

Table 4.2. The results of simple tests to distinguish the three main rock groups

Observation/test Rock group	Examination of grains/ crystals	Permeability test	Scratch test
Sedimentary	Grains cemented or compressed together	Water sinks in or streams of bubbles rise from specimen, unless fine-grained or well cemented	Easily scratched unless well-cemented
Igneous	Crystals interlocking, randomly orientated	Water does not sink into surface; bubbles do not rise from specimen	Difficult to scratch unless well-weathered
Metamorphic	Crystals interlocking; randomly orientated if formed mainly by heat; parallel or sub-parallel if formed by pressure and heat together		

Box 4.2E. Prehistoric carvings on rock faces

Labyrinth carving, Rocky Valley, Cornwall

Cup and ring marks, Wallridge Moor, Northumberland

Rock art on Chattonpark Hill, Northumberland

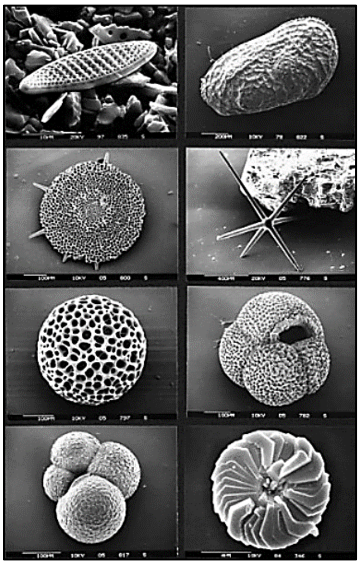
Rock carvings in England are usually described as rock art. They are not linked with any materials that can be dated, making them very difficult to date. Most are thought to have been carved between 3800 and 1500BCE which, archaeologically is the late Stone Age and the Early Bronze Age in England. There are around 2500 English rock art sites, mostly on exposed rock faces in northern England.

Chris King

4.1.1.3 Fossils

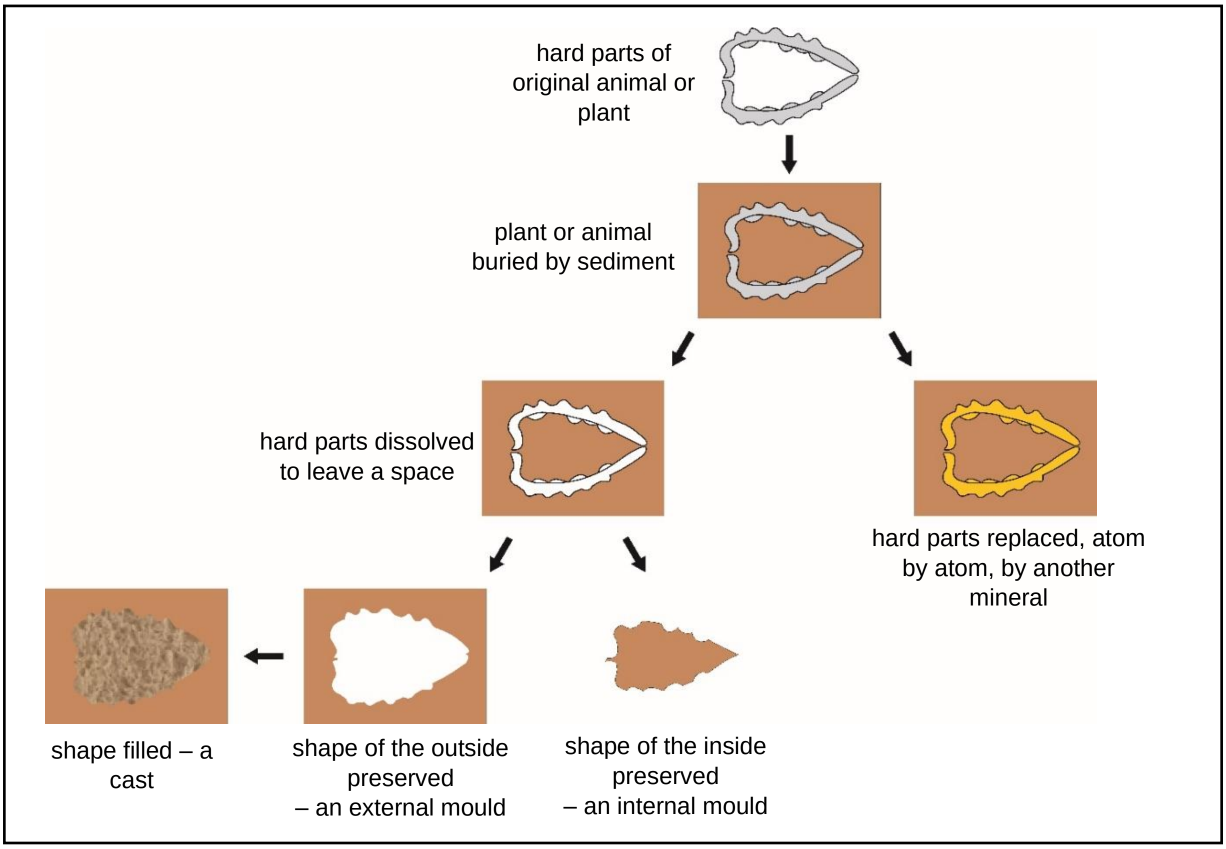
Fossils include any preserved trace of life and are usually considered to be more than 10,000 years old. They range in size from the largest dinosaurs to the smallest microfossils (Figure 4.2.).

Figure 4.2. Argentinosaurus from Argentina, the largest type of dinosaur known so far, and scanning electron microscope (SEM) images of tiny marine microfossils



Fossils are found in sedimentary rocks and some low-grade (not greatly metamorphosed) metamorphic rocks. They are the preserved remains of the hard parts of organisms such as shells or bones and very occasionally the soft organic parts (including skin, fur, feathers, etc). In some cases, the original materials have been replaced atom by atom by other minerals, which may or may not keep all the original features. Sometimes fossils have been dissolved away, leaving holes (moulds) in the surrounding rock. The moulds may have later been filled by other materials, forming casts of the original fossils (Figure 4.3.).

Figure 4.3. Fossilisation



Preserved evidence of the bodies of fossils are called **body fossils** while **trace fossils** are the signs left by organisms in sediment, such as footprints, burrows, borings and rootlet traces. Important modes of fossilisation are shown in Table 4.3.

Table 4.3. Important processes of fossilisation

Fossilisation process	Image	Fossil group
Burial – soft and hard parts preserved		Small shrew-like mammal fossil – showing bones and preserved fur Fossil from Yixian Formation, Liaoning Province, China early Cretaceous age
Burial – hard parts only preserved		A *Gryphaea* bivalve Fossil from Jurassic limestone in the Cotswolds, Gloucestershire
Replacement – original mineral replaced by a new mineral		Ammonite, originally formed of calcium carbonate, now pyrite Fossil from Lyme Regis, Dorset, Jurassic age

Table 4.3. Important processes of fossilisation, continued

Fossilisation process	Image	Fossil group
Mould-formation		The internal and external moulds of snail-like gastropods (the fossils themselves have been dissolved away, leaving the shape of the inside and outside of the shell) Fossils in Portland Stone, a Jurassic building stone from Portland in Dorset. The stone is used here for the offices of the *Economist* newspaper in London
Cast-formation		Cast of a dinosaur footprint; the dinosaur made a footprint in mud which became hardened before it was filled with sand; now the mud has been removed and the sandstone turned upside down to reveal the sandstone cast Fossil from Ashdown Formation, Fairlight, Sussex Cretaceous age
Trace fossils – burrows and trails		Burrows in Carboniferous mudstone Fossils from Cocklawburn beach, Northumberland
Trace fossils – rootlet traces		Rootlet traces – probably of reed or marsh plants, Saint Hill near East Grinstead in West Sussex Cretaceous age

Box 4.3E. Chirotherium tracks – a fossil mystery that took more than a century to solve

Plaster cast of Chirotherium footprints, a large hind foot and a much smaller front foot

Chirotherium tracks

Building stone was being quarried in Wirral in Cheshire when, in 1838, the quarry workers discovered outlines of what looked like human hands on some of the sandstone slabs. They thought the marks had been left behind by drowned animals of Noah's Flood. Scientists disagreed and decided that they were like fossil footprints found in Germany a few years earlier, which had been given the name Chirotherium. This means 'hand beast' from two Greek words, *cheir* (hand) and *therion* (beast). Each footprint looked like a human hand with five toes, four pointed forward while the other was a thumb-like toe to one side.

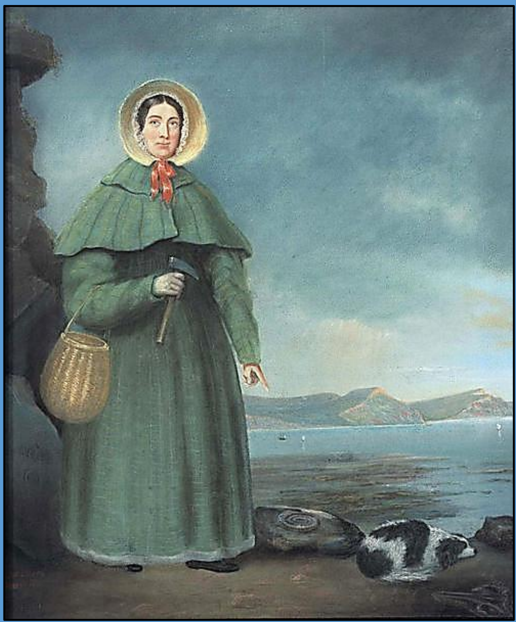
The Triassic sandstone that was being quarried formed in a tropical desert area about 240 million years ago. Temporary lakes formed in low-lying areas after rainstorms and as the lakes dried out, creatures left footprints in the mud. Desert sand later blew across the dried-up bed of the lake and filled the footprint hollows, preserving the tracks and trails.

The rock in which the Chirotherium footprints are preserved contains no fossil remains like teeth or bones, to give a clue to the kind of animal that left the traces. Different ideas about what the animal might be, included a giant marsupial by Alexander von Humboldt and J. J. Kraup (1835) and an amphibian by Richard Owen (1842). In 1925, Wolfgang Soergel, correctly suggested that the Chirotherium prints were produced by a distant relative of modern crocodiles.

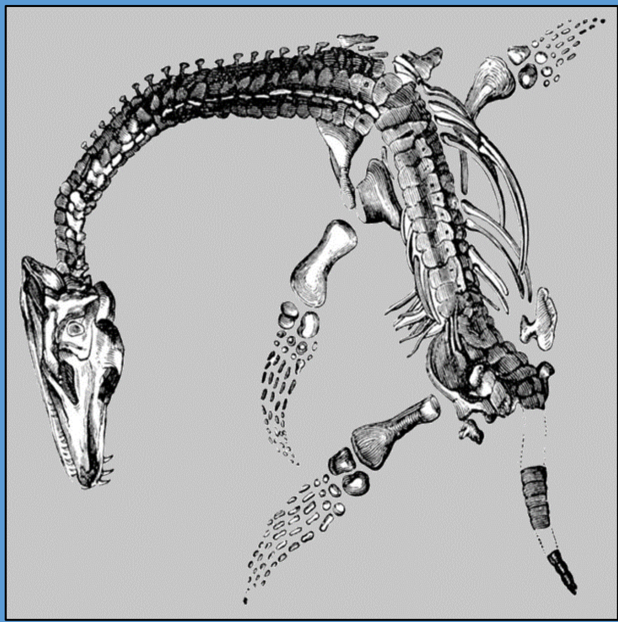
The mystery was not solved until 1965 when a skeleton of what we now think is the trackmaker was finally found. This skeleton was a reptile called *Ticinosuchus*, exactly fitting Soergel's predictions. *Ticinosuchus*, or a close relative, seems to have been the true Chirotherium trackmaker, a crocodile-like animal making tracks at about the time when the first dinosaurs evolved.

Maggie Williams

Box 4.3E. Mary Anning, 'a woman in a man's world'



Mary Anning with her dog Tray on Lyme Regis beach in Dorset, 1842



The plesiosaur skeleton found by Mary and Joseph Anning in 1830

Mary Anning was the first famous female fossil hunter and found spectacular fossils in the cliffs of southern England in the early 1800s. She was born in Lyme Regis in Dorset to a poor family. She collected fossils with her father and her brother so they could sell them. She left school at age 11 when her father died, so she could sell fossils to give the family its only income. Mary never married and worked alone with her dog for company. She went out in rain or sun to see what nature had provided for her on the beach and in the crumbling cliffs of Jurassic rock.

In 1820 Mary found her first plesiosaur skeleton and another more complete one in 1830. In 1828 she discovered parts of the first pterodactyl ever found in Britain. She thought it had been a flying reptile.

Mary was in touch with famous geologists of the time, including William Buckland, Henry de la Beche and George Cuvier. She never left Lyme Regis but many famous people visited her. It saddened her that her work was not widely recognised and none of her museum specimens were credited to her as the finder. In the early 1800s few women were scientists and many people thought that women's brains were poorer than men's. At this time the Bible was used to interpret scientific ideas and the idea of extinct unknown animals and evolutionary change were unimaginable ideas to most people, making it much more difficult for Mary to be recognised.

All her specimens shown in the Natural History Museum in London, are now credited to her name.

Elizabeth Devon

4.1.1.4 Sedimentary rocks

Sedimentary rocks were laid down as sediments, and are identified using their mineral composition and grain size (Table 4.4). Sedimentary rocks are usually permeable unless they are well cemented or fine-grained, and most are easy to scratch. The grains are easy to see in sand-grade rocks, but usually impossible to see in mud-grade rocks, even with a hand lens.

Table 4.4. Classification of sedimentary rocks

Chemical composition		Silicon-rich	Calcium carbonate-rich	Sodium chloride-rich	Carbon-rich
Characteristics		The most common sedimentary rocks; resistant if well cemented, otherwise easy to scratch; commonly dark or pale grey, brown, cream or red	React with dilute hydrochloric acid; easy to scratch; commonly pale grey, cream or white	Made of halite with salty taste; cubic crystals; very easy to scratch; pink, white or colourless	Very easy to scratch; often break into cubic shapes; black; may contain plant fossils
		Common rock types – see Table 4.5			
Grain size	Fine < 0.0625 mm	Mudstone; shale; clay; claystone	Limestone; chalk	Rock salt	Coal
	Medium 0.0625 – 2 mm	Sandstone; siltstone	Limestone		
	Coarse > 2 mm	Conglomerate; breccia			

Most sand-grade sediments are laid down in beds, whilst muds are deposited in thinner layers called laminations. As the sediment became buried, muds became compressed into more compact mudstones, shales or clays/claystones and lime mud was compressed into limestone or chalk, as water was squeezed out. Meanwhile water flowed through the pore spaces of coarser sediments, such as pebble beds, sands and shell sands, and minerals crystallised from the water as a natural cement, which glued the grains together; these sediments became lithified into coarse-grained conglomerates and medium-grained sandstones or limestones, as shown in Table 4.5. So, for sedimentary rocks, the two main rock-forming processes are **compaction** and **cementation**.

Table 4.5. Common sedimentary rocks

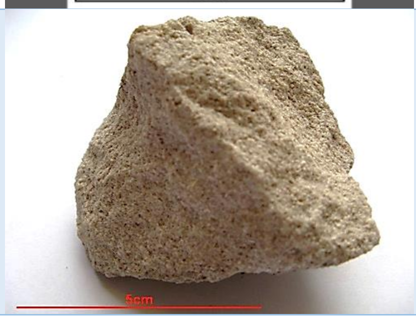
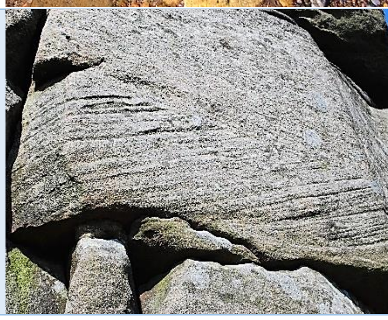
Sedimentary rock	Images		Source of exposure image
	Specimen	Exposure	
Conglomerate			Conglomerate with large pebbles on a wave-cut platform, Goldsborough, North Yorkshire Jurassic age
Buff-coloured sandstone			Cross-bedded buff-coloured sandstone, on Burbage Edge, near Sheffield, Yorkshire Carboniferous age

Table 4.5. Common sedimentary rocks, continued

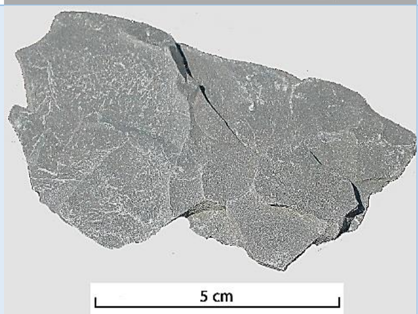
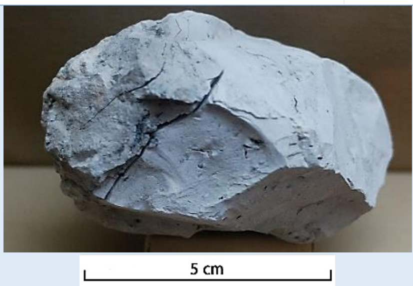
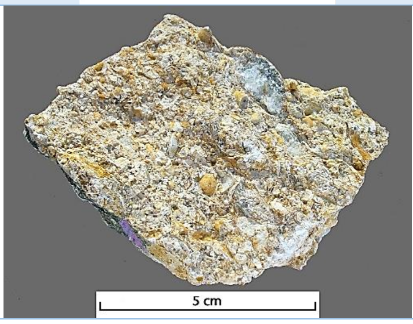
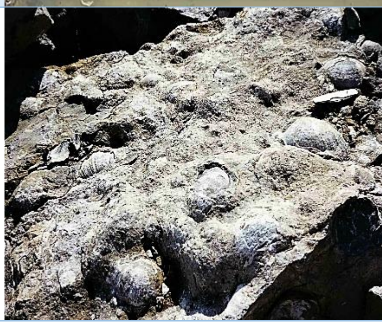
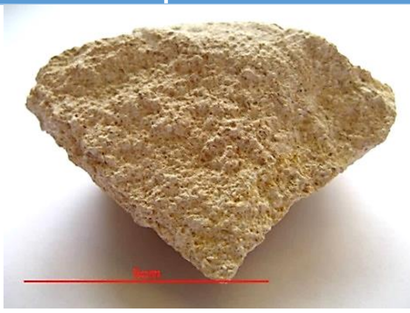
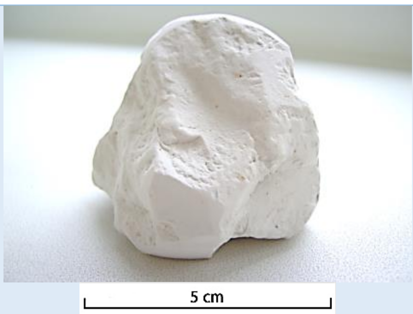
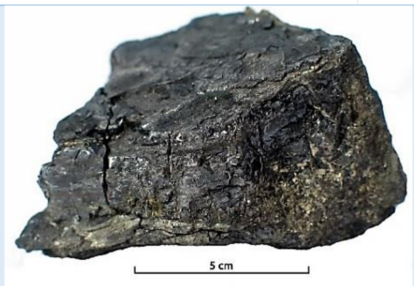
Sedimentary rock	Images		Source of exposure image
	Specimen	Exposure	
Red sandstone			Cross-bedded red sandstone near Dawlish, Devon Triassic age
Mudstone			Mudstone in a former brick pit, Sheffield, Yorkshire Carboniferous age
Shale			Shale exposure on the bank of Burbage Brook, Derbyshire. Carboniferous age
Clay			Brown clay in the Coal Measures, Sheffield Carboniferous age
Fossiliferous limestone			Brachiopod shells in limestone, Monyash, Derbyshire Carboniferous age

Table 4.5. Common sedimentary rocks, continued

Sedimentary rock	Images		Source of exposure image
	Specimen	Exposure	
Oolitic limestone			Oolitic limestone cliffs near Burton Bradstock, Dorset Jurassic age
Chalk			Chalk cliff and boulder with flint nodules, Swyre Head, West Lulworth, Dorset Cretaceous age
Rock salt			Rock salt in Boulby Mine, North Yorkshire. Natural exposures of salt are only found underground, since salt dissolves in water
Coal			Blindwells Opencast Coal site, Tranent, East Lothian, Scotland. The opencasting has exposed the pillars of the old deep coalmine Carboniferous age

Box 4.2. An unusual sedimentary rock – chert (or flint)

Box 4.2. An unusual sedimentary rock – chert (or flint), continued

Chert is found as lumps called nodules in fine-grained limestone (right-hand photo). When it is found in chalk it is called flint (left-hand photo) and was used in prehistoric times to make arrowheads and other sharp tools.

Chert and flint are formed when fine lime mud is laid down in quiet conditions on the sea bed and dead microscopic organisms made of silica (silicon dioxide) are deposited at the same time. As the lime mud is being compressed into limestone or chalk, the silica dissolves in the water between the particles. It then recrystallises into very fine-grained chert/flint nodules, which grow in the rock over time. The nodules have odd rounded shapes and sizes and are often found in layers. Beaches beneath chalk cliffs are usually made of very hard flint pebbles as the chalk is eroded away by the sea.

4.1.1.5 Igneous rocks

Igneous rocks formed from once-molten magma, either as the magma cooled and crystallised or as it erupted explosively from a volcano. Most igneous rocks are impermeable and resist scratching because of their interlocking crystals; they are identified using their crystal size and chemical composition. The crystals in coarse-grained rocks are easy to see, those in medium-grained rocks need a hand lens, and the crystals in fine-grained rocks are usually impossible to see without a microscope. Coarse-grained rocks formed by slow cooling of magma deep beneath the surface are called **plutonic rocks**; fine-grained igneous rocks were erupted as **volcanic rocks**.

The chemical composition of the rock is linked to the minerals present and these produce the overall colour of the rock. Rocks that are rich in iron and magnesium have dark-coloured iron/magnesium-rich minerals whilst silicon-rich rocks have mainly pale-coloured minerals like feldspar and quartz. This gives the classification system in Table 4.6.

Table 4.6. Classification of igneous rocks

Chemical composition		Iron/magnesium-rich	Intermediate	Silicon-rich
Characteristics		Dark minerals; dark in colour; higher density (feel heavy)	Intermediate characteristics	Pale minerals; pale in colour; normal rock density
		Common rock types – see Table 4.7		
Crystal size	Fine (< 1mm)	Basalt	Andesite	Volcanic ash
	Medium (1-3mm)	Dolerite	Uncommon	Uncommon
	Coarse (>3mm)	Gabbro	Uncommon	Granite

Table 4.7. Common igneous rocks

Igneous rock	Image		Source of exposure image
	Specimen	Exposure	
Granite			Tor on Dartmoor of the Dartmoor granite, intruded around 280Ma during the Permian period

Table 4.7. Common igneous rocks, continued

Igneous rock	Image		Source of exposure image
	Specimen	Exposure	
Gabbro			The Carrock Fell gabbro, intruded around 450Ma during Ordovician times. Carrock Fell, Cumbria.
Dolerite			The 300Ma dolerite Whin Sill intrusion is used as a defensive position by Bamburgh Castle in Northumberland
Basalt			Exposures of Carboniferous polygonal basalt columns in Borthwick Quarry, Duns, Scottish Border near Berwick-upon-Tweed
Andesite			Andesite lava of Ordovician age exposed at Joppléty How, Borrowdale, Cumbria
Volcanic ash			Layers of Carboniferous volcanic ash above an explosive deposit of volcanic blocks and ash, Weston-Super-Mare, Somerset

Box 4.3. An unusual igneous rock – volcanic glass

Like other igneous rocks, volcanic glass is formed by cooling magma. When magma cools slowly underground, there is time for large crystals to form. When it is erupted as lava at the surface, it cools down much more quickly, and so has much smaller crystals, like the fine-grained lava, basalt. If it cools down more quickly still, there is no time for the atoms in the liquid to gather together in crystals, and glass is formed. The volcanic glass in this lava flow, specimen and prehistoric knife formed like this. Window and bottle glass are made by chilling molten silica in the same way.

4.1.1.6 Metamorphic rocks

Metamorphic rocks are formed when sedimentary, igneous or older metamorphic rocks recrystallise in the solid state under increased heat and/or pressure. Rocks do not melt during metamorphism, otherwise they would become igneous rocks.

Most metamorphic rocks result from the increased heat and pressure of the mountain-building caused by plate collision. This is **regional metamorphism**. Under the intense conditions, some minerals are transformed into other minerals, some minerals recrystallise to become thinner and longer, while other minerals rotate until they are lined up at right angles to the direction of the pressure.

Metamorphic rocks also form when rocks are baked by a nearby hot igneous body. Since the mineral recrystallisation here is mainly by heat, and there is no tectonic pressure, the crystals in the new rocks are randomly orientated.

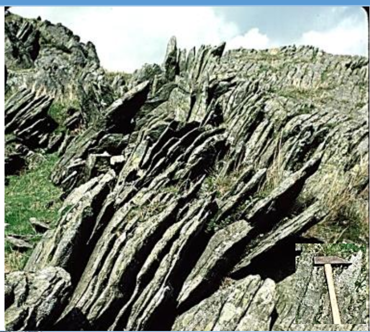
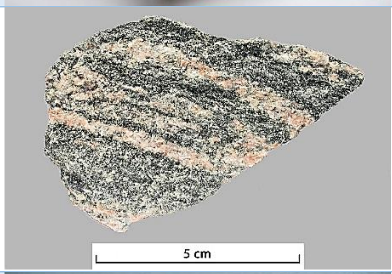
The type of metamorphic rock formed either by heat and pressure (regional metamorphism) or mainly by heat (**thermal metamorphism**) depends on the make-up of the rock it originally came from, as in Table 4.8.

Table 4.8. Classification of metamorphic rocks

Mineral composition		Quartz and clay minerals in mudstone or shale	Quartz in sandstone	Calcite in limestone
		Common regional metamorphic rock types – see Table 4.9		
Increase in heat and pressure ↓	Low-grade	Slate	Metaquartzite (or quartzite)	Marble
	Medium-grade	Schist		
	High-grade	Gneiss		
		Common thermal metamorphic rock types		
Increase in heat		Hornfels	Metaquartzite (or quartzite)	Marble

Since metamorphic rocks are made of interlocking crystals, they are usually impermeable and resist scratching more than most sedimentary rocks. The regional metamorphic rocks can be identified from their aligned minerals. In fine-grained slate, they produce weaknesses in the rock, which can be broken into thin sheets along the weaknesses or cleavage planes. In coarser-grained schist, the aligned minerals can be seen reflecting the light in flashes when a specimen is moved. The minerals form bands in gneiss; sometimes the bands are deformed into complex folds. It is difficult to see any mineral alignment in metaquartzite or marble and so difficult to tell regional from thermal metamorphic metaquartzite and marble. Metaquartzite is like an impermeable hard, sugary sandstone; marble also can look sugary, but reacts with dilute hydrochloric acid. Hornfels is also hard and, being a thermal metamorphic rock, is formed of randomly orientated minerals, but these are usually impossible to see in this fine-grained rock.

Table 4.9. Common metamorphic rocks

Metamorphic rock	Images		Source of exposure image
	Specimen	Exposure	
Slate			Borrowdale Slates, Dunnerdale, Cumbria Ordovician age
Schist			Hornblende schists forming the cliffs at Lizard Point, Cornwall Probably Cambrian in age
Gneiss			Banded gneiss exposed on Kennack Sands, The Lizard, Cornwall Devonian age
Marble			Marble block in Carrara quarry, Italy – widely used as a building stone and for sculpting statues Jurassic age
Metaquartzite (quartzite)			Metaquartzite. Breakwater Country Park, near Holyhead, Anglesey Precambrian age

4.1.1.7 Soil

Soil results from the interaction between life and Earth's surface materials – so where there is no life, there is no soil. Soil forms through interactions between the solid geosphere, the hydrosphere, the atmosphere and the biosphere. Soils form on loose surface materials like river or glacial deposits or by the biological weathering of bedrock. The many different soils that can form depend on many factors, including climate, altitude, steepness of slope and the type of bedrock or other surface material.

Soils nearly always have a surface layer or topsoil that is usually dark in colour. The surface layer is the main zone of plant roots; many microorganisms and animals like worms live there and it is where most decaying organic material or humus is found. The main constituents of topsoil are therefore: animal and plant life, humus, sediment or rock fragments, water and air. Small amounts of topsoil contain billions of microscopic plants and animals belonging to thousands of different species.

Below the surface layer in most soils is a subsoil zone where fine-grained material builds up after being washed downwards by soil water; most of the chemical changes happen here. The base of a soil is the bedrock or other original surface material.

Soil is a key part of Earth's ecosystem; all large plants grow in soil. It is a key habitat for a wide range of other plants and animals, and is the basis of all agriculture. It recycles nutrients and organic waste and affects the quality of water flowing through. Soil also interacts with the gases of the atmosphere. The best topsoil for plant growth is around half solid material and half space, filled by water or air. The solid material is a mixture of sand, silt and organic humus; different mixes of sand, silt, clay and humus give a range of different soil types.

Figure 4.4. Soil sequence on the Great Ouse floodplain, near Renhold, Bedfordshire

Farmers try to make soils more productive by adding different constituents. In areas where soils are acid, lime (calcium oxide/hydroxide – $CaO/Ca(OH)_2$) is added to neutralise them. In other areas adding clays improves soils, while elsewhere, adding animal manure or potassium and nitrogen fertilizers increases soil productivity.

Box 4.4. Charles Darwin and soil

Charles Darwin was one of the first people to understand how important earthworms are to soil-formation. He had noticed that a layer of white calcium carbonate lime that had been put on soil in an English field many years before now formed a layer several centimetres underground. He worked out that this must be due to the action of earthworms and built his own wormery to investigate his idea. He published his ideas about the importance of earthworms to soil-formation in 1881.

Photos of a home-made wormery in a cut-off plastic bottle – before adding earthworms and afterwards, following several days of earthworm activity.

4.1.2 Earth's processes and observed characteristics

Earth processes are linked together through the rock cycle, shown in Figure 1.7. The rock cycle includes the surface processes of weathering, erosion, transportation and deposition that are closely linked to the surface part of the water cycle. After sediments are deposited, they can become buried by overlying sediments when compaction and the crystallisation of natural cement transforms them into sedimentary rocks.

Plate tectonic processes drive the internal part of the rock cycle, deforming rocks, causing metamorphism, igneous activity and uplifting rocks to the surface, where they are attacked by surface processes again.

4.1.2.1 Surface processes

The atmosphere, hydrosphere and biosphere interact with the geosphere, moulding the landscape and forming and depositing sediment. Surface rocks are attacked by weathering and erosion. **Weathering** is the break-up (physical break-up) and breakdown (chemical breakdown) of material at the Earth's surface without the removal of solid material. **Erosion** is the removal of solid material, which can then be transported further away.

Although weathering processes tend to act together, they can be divided into separate physical, chemical and biological effects, as shown in Table 4.10.

Table 4.10. Common weathering processes

Process		Description	Image	Source
Physical	Freeze/thaw	Water enters cracks, freezes, expands, then thaws and trickles deeper; as freeze/ thaw cycles continue, the crack is widened. Important where freezing/ thawing is common, as on mountain tops		Freeze-thaw fracturing in a limestone block on a wall, Grindleford, Derbyshire
	Heating/ cooling	Rocks become very hot during the day and very cold at night; since the minerals expand and contract at different rates, the rock is weakened and cracks. Important in hot regions that become very cold at night		Sheets of granite breaking away due to heating/cooling, Half Dome, Yosemite National Park, USA

Table 4.10. Common weathering processes, continued

Process		Description	Image	Source
Chemical	Acidic water on limestone and marble	Rainwater dissolves carbon dioxide from the atmosphere and takes in more CO_2 as it flows through soil. The weak carbonic acid dissolves calcium carbonate. When limestone is dissolved along joints, they become wider and caves can form		Carboniferous limestone pavement with widened joints (grykes), Austwick, North Yorkshire
	Oxidation of sandstone and quartzite	Rainwater flows along joints, oxidising (rusting) iron minerals to bright yellow, brown and red colours		Oxidation weathering to a surface rusty colour. Carboniferous mudstones, Neepsend Brickpit, Sheffield, Yorkshire
Biological	Lichens and mosses	Lichens are the first plants to colonise bare rock. Their tiny rootlets grow into the pores between rock grains, and weaken the rock as the lichen dries and contracts. They also have biochemical effects. Lichens are often followed by mosses, then soil		Lichens growing on a sandstone gatepost, Sheffield, Yorkshire
	Soil-formation	Biological effects of weathering on bedrock produce soil		Soil profile on a clifftop, Gower, Wales

Erosion is the removal of solid material. Landscapes are moulded and sediments are formed by four major processes of erosion, as highlighted in Table 4.11.

Table 4.11. Important erosional processes

Process	Description	Image	Source
Moving water (in rivers and the sea)	Flowing water picks up and erodes particles and also carries sediment that erodes bedrock. Most erosion occurs during floods, when riverbanks can fail catastrophically		Bank collapse due to undercutting by erosion of the Skell River near Ripon, Yorkshire
	Waves and the sediment they carry erode the foot of coastal cliffs, often causing rockfalls. These later become broken up by the waves		Beach closed by a coastal erosion rockfall, Oddicombe, Devon
Gravity	Rock fragments, often weakened by weathering, fall off because of gravity Large-scale rockfall produces sloping screes which have cone-shapes under gullies. Erosion by gravity includes rockfall and the sliding rocks of landslides		Wast Water screes, Cumbria
Moving air (wind)	Wind erodes sand-sized, silt and mud-sized particles; the sand may form local sand dunes but silt and mud may be carried far away as dust clouds		Dust storm over a newly ploughed field, Rufford, Nottinghamshire
	Wind erosion of a rock outcrop; in a strong wind more sand grains hit and erode the base of the outcrop than the top, which is why the base is so narrow		A wind-eroded rock at Bridestones on the North York Moors, Yorkshire
Moving ice	Although ice itself cannot erode bedrock, the sediment it carries can. As ice sheets or glaciers move, the bedrock becomes eroded in the direction of the ice-movement, cutting scratch-marks or striations. The debris carried by the ice is ground down at the same time		Bedrock scratched by a glacier carrying rock debris, Austwick, North Yorkshire

Together, weathering and erosion shape the landscape. The resistance of rocks to weathering and erosion depends on how chemically stable the minerals are at the Earth's surface, and how the grains of the rock are interlinked. Rocks formed of interlocking crystals and of well cemented grains tend to resist erosion, and form higher land, coastal cliffs and headlands, whilst less resistant rocks form valleys and bays. The angle of dip of resistant rocks and other geological features often control the shape of the landscape, producing a variety of landforms and coastal features (Table 4.12).

Table 4.12. Landforms formed by resistant rock layers

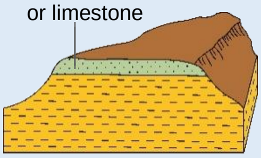
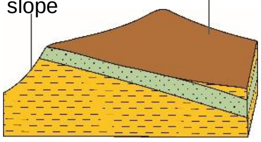
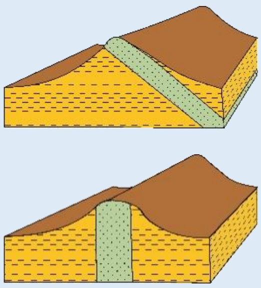
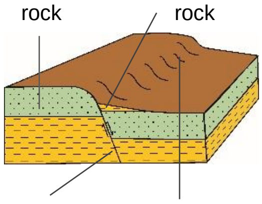
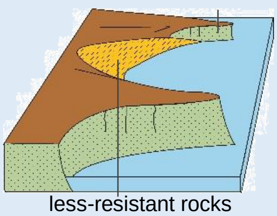
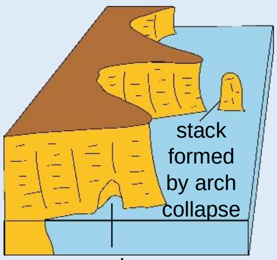
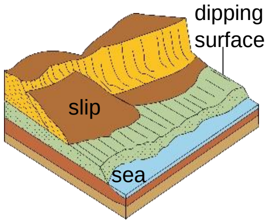
<table>
<tr><th>Landform</th><th>Description</th><th>Drawing</th><th>Image</th><th>Source</th></tr>
<tr><td>Plateau</td><td>Plateaus have flat tops and steeper sides. They are formed when resistant rocks are horizontal or near horizontal (plateaus can also be formed as erosion surfaces over different rocks)</td><td></td><td></td><td>Ingle-borough plateau from Simon Fell, North Yorkshire</td></tr>
<tr><td>Cuesta</td><td>Cuestas have a steeper slope in one direction and a shallower slope in the other direction. They form when resistant rocks have a shallow slope (dip)</td><td></td><td></td><td>Stanage Edge cuesta from Burbage Derbyshire</td></tr>
<tr><td>Ridge</td><td>Ridges have steep slopes in two directions and form when resistant rocks dip steeply or are vertical</td><td></td><td></td><td>The East Ridge of Bannerdale Crags, near Scales, Cumbria</td></tr>
<tr><td>Fault scarp</td><td>When the rocks on one side of a fault are more resistant than the other, a fault scarp often forms</td><td></td><td></td><td>The Long Mynd fault scarp, with resistant older rocks in the background in Shropshire</td></tr>
<tr><td>Headland and bay</td><td>When some coastal rocks are more resistant than others, headlands and bays form</td><td></td><td></td><td>Robin Hoods Bay, North Yorkshire</td></tr>
</table>

Table 4.12. Landforms formed by resistant rock layers, continued

Landform	Description	Drawing	Image	Source
Coastal cliff	Where resistant rocks are horizontal or slope (dip) away from the sea, steep cliffs normally form, often with features like arches and stacks			Coastal cliff and stack with arches to the left and right, Sidmouth, Devon
Coastal slope	Where there are no resistant rocks, or the rock layers slope (dip) towards the sea, shallow coastal slopes usually develop			Slumping coastal cliffs, Shippards Chine, Isle of Wight

Box 4.5E. Plateau hill forts

Cadbury Castle hill fort, Somerset on a Jurassic limestone plateau

Oswestry hill fort in Shropshire on a Carboniferous sandstone plateau

Hambledon Hill Iron age hill fort in Dorset, built on a chalk plateau

The Iron Age in England was the time between 800 BCE and the Roman invasion in 43 CE. During that time, people often chose small plateaus as sites for their hill forts. They dug banks and ditches to protect the forts, often with wooden defensive walls on top of the banks. These defensive structures were built to protect local people at times of danger from war or conflict.

Chris King

Erosion is very active during high energy conditions like storms. After sediments are eroded, by gravity, moving water, wind or ice, they are transported; they are often deposited and eroded many times during transportation. Most permanent deposition occurs in quieter, low energy conditions. Some landscape features depend more on erosion and deposition than on the characteristics of the rocks beneath, as in Table 4.13.

Table 4.13. Landscape features formed mainly by erosion and deposition

Process		Description	Image	Source
Erosion	by moving water	Flowing water erodes bedrock at the base of upland valleys, making them deeper. As material slides down the sides, they often become V-shaped		V-shaped Carding Mill Valley, Long Mynd, Shropshire
Erosion	by moving ice	Glaciers flowing down upland valleys erode both the sides and base of the valleys, producing U-shaped valleys		U-shaped glacial valley on the River Swale in North Yorkshire
Deposition	by water on flood plains	When rivers flood, the water flows across flood plains on either side, depositing layers of mud and silt. The mud layers build up into broad flat flood plains with river channels meandering across them		Meandering River Wampool, near Whitrigg, Cumbria
Deposition	by water in lakes and seas	Rivers carrying sediment into lakes and quiet seas deposit the sediments, building deltas which are often fan-shaped		River Derwent delta building out into Derwent Water, Cumbria
Deposition	by melting ice	Melting ice deposits mixtures of boulders and clay (till) at the ends and sides of glaciers and where melting ice sheets have been; the hummocky deposits are called moraine		Glacial moraine making hummocky ground in Deepdale U-shaped valley near Hartsop, Cumbria

Nowadays, humans may move more sediment each year than all the world's rivers put together, through mining, quarrying, construction and agriculture. Despite this, most landscape-formation remains natural and that always will be so.

4.1.2.2 Sedimentary processes

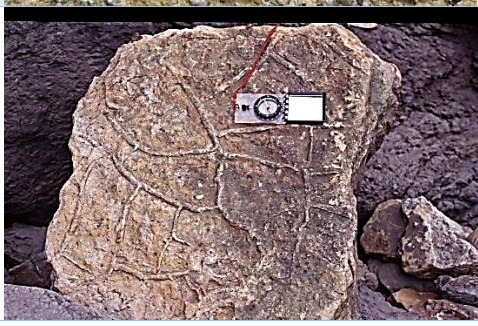
Weathering and erosion produce sediment, which is broken down during transportation. Rock fragments become rounded. Less stable minerals break down, usually to clay minerals, while more stable minerals, like quartz, become ground down. Under quieter conditions, rock fragments, quartz, clay and other minerals are deposited and sediments build up. Lime sands and muds, formed of calcium carbonate minerals, are usually deposited in warm shallow seas in tropical and sub-tropical areas and can later become lithified into limestone.

Sediments form a range of sedimentary structures as they are deposited, which give evidence of how they were laid down, as shown in Table 4.14.

Table 4.14. Important sedimentary structures

Sedimentary structure	Description	Image	Source
Bedding	Sediment is not usually laid down steadily, but often each layer is deposited in a rush, with quieter times or even erosion in between. The layers in medium- and coarse-grained sediments are called **beds**; the rocks are bedded		Horizontally bedded Carboniferous limestones of different thicknesses at Cullernose Point, Northumber-land
Lamination	Muds are also often laid down in layers, but these are much thinner layers called **laminations**		Laminated mudstone above/below an uneven sandstone bed in the Carboniferous Bowland Shales, Collyholme Wood, Lancashire
Cross-bedding	Cross-bedding forms when sand is laid down in dunes. Sand is carried up one side of the dune and cascades down the front as a series of beds sloping down-current. Water-formed dunes produce small-scale cross beds usually less than 1m thick, whilst winds produce dune cross-bedding that can be several metres thick		Wind-formed cross-bedded Permian sandstone, Dawlish, Devon

Table 4.14. Important sedimentary structures, continued

Sedimentary structure	Description	Image	Source
Asymmetrical ripple marks	Water currents over sand, slower than the ones that form cross-bedding, form asymmetrical ripple marks instead. Water flows up the shallow side and deposits sand on the steeper side of the ripples. Water-formed ripple marks can be in lobes or straight lines, but wind-formed asymmetrical ripple marks are usually straight		Asymmetrical ripple marks in Carboniferous sandstone, Brincliffe Edge, Sheffield, Yorkshire; current from top left to bottom right
Symmetrical ripple marks	Symmetrical ripple marks are formed in shallow water by waves. The ripple marks have equal slopes on either side and usually form in straight parallel lines. The crests of the waves that form the ripple marks are parallel to them and are often also parallel to the coast		Symmetrical ripple marks in Cretaceous sandstone near Partridge Green, West Sussex; ancient coastline from left to right
Graded bedding	When a current carrying sediments of mixed sizes slows down, the largest particles are deposited first and then finer and finer grains are laid down on top, forming a single bed of sediments that grades from coarse at the bottom to fine at the top; graded bedding can be used to show that a sediment sequence has not been turned upside down by folding		Graded bedding – Eocene grit in a garden wall near Besalú in Catalonia, Spain
Desiccation cracks (mud cracks)	When mud dries out, it cracks into polygonal shapes; if the cracks later become filled by sand, they are often preserved. These desiccation cracks show that the mud must have dried out, so cannot be a deep-sea mud		Desiccation cracks formed by sand filling mudcracks in the bed below, Jurassic sandstone, Whitby, Yorkshire

If sediments are laid down in subsiding regions, they can become thick sedimentary sequences. After burial, fine sediments are compacted and coarser sediments are compressed and cemented into sedimentary rocks.

Much later, plate tectonic movement may uplift the sedimentary rock sequence. As the uplifted sedimentary rocks are eroded, the sediment becomes part of the sedimentary cycle again. The sedimentary cycle is one part of the rock cycle.

Box 4.6E. Abandoned millstones.

Abandoned millstones on Stanage Edge, Derbyshire

For centuries, the coarse gritstones of the Carboniferous Millstone Grit Series of rocks in the Peak District were used to make millstones for grinding grain for flour and for animal food. But why are there so many abandoned millstones lying around the gritstone "edges" today? Around the beginning of the 20th Century, Britain began importing "hard" wheat grain from the newly opened up Prairies and Great Plains of North America, and it was found that steam-driven steel roller mills could cope better with the harder grain. They could also produce a whiter bread flour, which became more fashionable. It made economic sense to locate the main flour mills at the ports, whether coastal, or along major rivers. The millstone makers were then left with hundreds of surplus stones on their hands as the 'bottom fell out of the industry'. As late as the 1970s, one major quarry in Derbyshire was cutting two huge pairs of stones annually for a wood pulp mill in Philadelphia, USA, but this trade too has ended.

Peter Kennett

4.1.2.3 Igneous processes

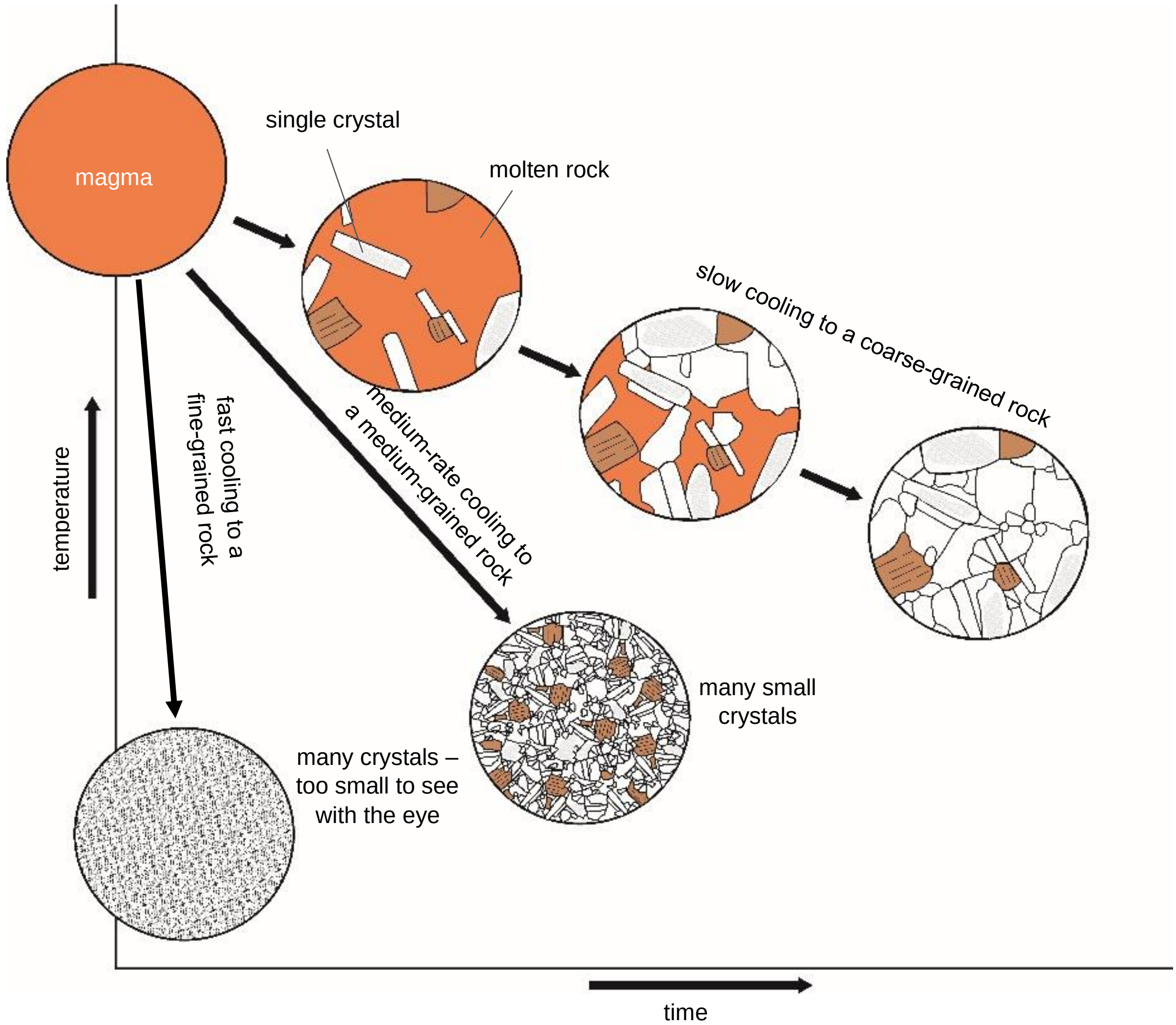
When rocks become hot enough, they melt. Since rocks are usually a mixture of minerals, they often do not melt entirely but only partially melt, with the lowest-melting point minerals melting first. If the magma produced by **partial melting** flows away, it has a different chemical composition from the original rock, because the higher-melting point minerals are left behind. So partial melting processes produce a range of different magmas with different compositions.

Iron and magnesium-rich melts form from the minerals with the highest melting points, and so crystallise at high temperatures, usually well over 1000°C. Silicon-rich melts, however, have lower melting point minerals, and so crystallise at lower temperatures, usually below 1000°C. This affects how runny the melts are (their viscosity) and the igneous processes that occur. Molten magma forms deep underground and, because it is hotter and less dense than the surrounding rock, it rises.

The temperature at which rocks melt does not depend on the melting points of the minerals alone, but also on the amount of water present and the pressure of the overlying rocks. Rocks melt at lower temperatures when they are 'wet' and when pressure is reduced. Igneous processes are active in both oceanic and continental areas, but the magmas, pressures, water content and other factors differ, and so the igneous bodies produced also differ.

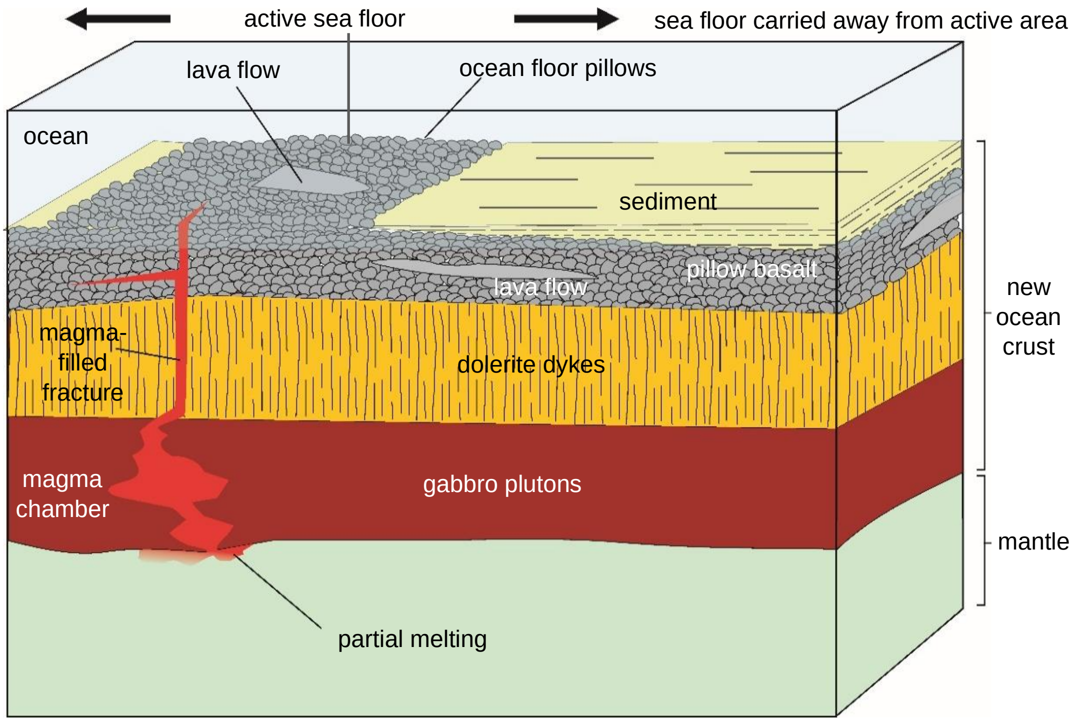
Rising magmas may stop deep underground, cool down and crystallise in **magma chambers**. The magma has plenty of time to cool and for crystals to grow in the cooling melt. The result is a coarse-grained igneous rock. If the magma rises higher it becomes cooler and so crystallises more quickly, into medium-grained rock. If it rises right to the surface, it is erupted by volcanic activity. Lavas formed like this cool down very quickly into fine-grained igneous rocks (Figure 4.5).

Figure 4.5. The cooling and crystallisation of igneous rocks



Under oceans, where tectonic plates are moving apart, the solid mantle beneath is very hot and so flows very slowly upwards. In flowing upwards, pressure is reduced and so the very iron/magnesium-rich mantle partially melts into magmas that are still iron/magnesium-rich. These rise, and some cool down slowly in magma chambers to form coarse-grained gabbro plutons at the base of the newly forming oceanic crust. These iron/magnesium-rich magmas are very runny (low viscosity) and so some continue to rise through fractures. These cool down more quickly into medium-grained dolerites, as dykes. Other magmas rise to the ocean floor and flow out as lavas, usually with pillow shapes (pillow lava). This usually produces new oceanic crust of iron/magnesium-rich igneous rocks, with coarse gabbro at the base, vertical sheets of medium-grained dolerite above, and layers of fine-grained pillow basalt at the surface (Figure 4.6).

Figure 4.6. Igneous bodies in oceans



Beneath continents, in areas where tectonic plates are converging, rocks become heated up. Water in the rocks lowers the melting point, causing them to partially melt. The magmas that form depend upon which rocks melt, so that a range of magma chemical compositions is possible. Some melts are rich in iron/magnesium, some are intermediate between iron/magnesium and silicon-rich types; the most common magmas are silicon-rich.

Silicon-rich magmas are very viscous (not very runny) and so mostly do not reach the surface, but crystallise slowly in magma chambers underground as coarse-grained granites. If they do reach the surface, being viscous, they mostly erupt explosively, producing widespread volcanic ash. Intermediate magmas also erupt explosively but flow out of volcanoes as lavas as well, to cool as fine-grained andesites. Any iron/magnesium-rich magmas usually erupt as basalts. The tubes that connect volcanoes with their feeder magma chambers are called **volcanic pipes**, which are sometimes exposed at the surface after erosion as **volcanic plugs**.

Between deep magma chambers and surface volcanoes, magmas can be injected into the surrounding rocks. If they cut across the rock layers, they are **dykes**; if they follow the layers, they are **sills**. Underground magma chambers that have crystallised are usually bubble-shaped and are called **plutons** if small and **batholiths** if large (Figure 4.7). Batholiths, plutons, dykes and sills are grouped together as **intrusive igneous rocks**, because the magma has intruded into the surrounding bedrock. Those at the surface are **extrusive igneous rocks**, since they have been extruded out onto the surface. The different features produced by these processes are shown in Table 4.15.

Figure 4.7. Igneous bodies on continents

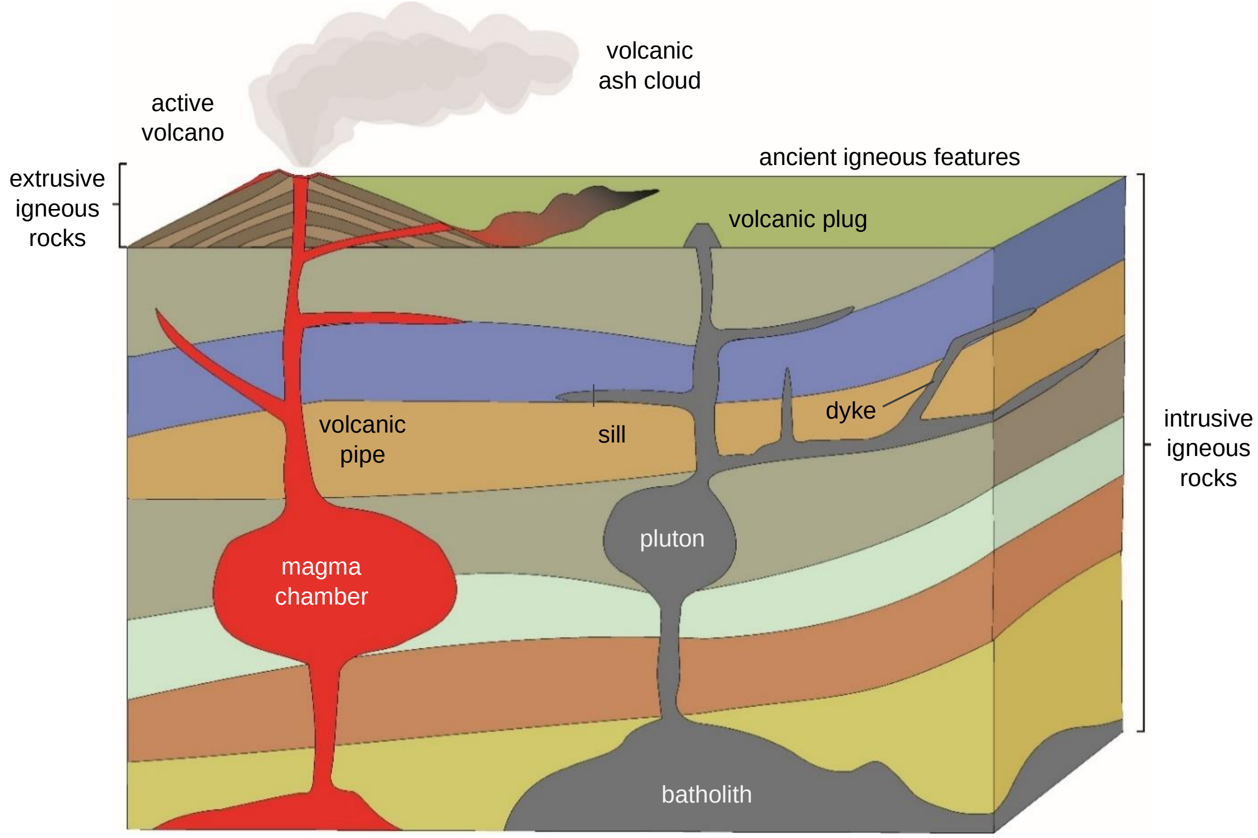
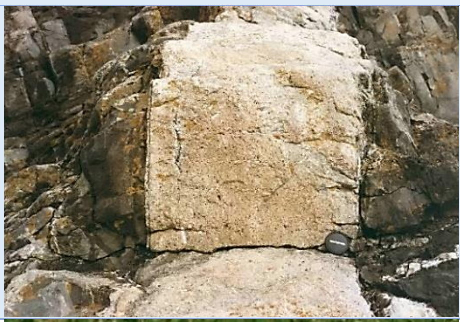


Table 4.15. Important igneous features

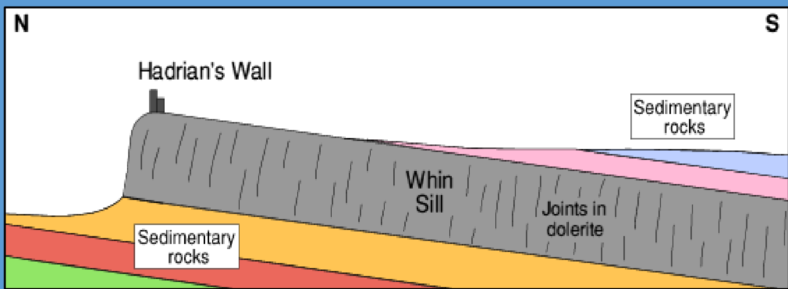
Igneous feature	Description	Image	Source
Modern pillow lava	When fluid basalts are erupted (extruded) into water, as on the ocean floor, small tongues of magma flow out and the outer parts become solid; the flexible solid acts like a bag which fills up with lava in pillow-like shapes		Modern pillow lavas on the ocean floor photographed during the Galapagos Rift Expedition in the west Pacific Ocean, 2002
Ancient pillow lava	When ancient pillows break in half, the finer-grained basalt of the margins can often be seen.		Pillow lavas compressed in a mountain-building episode. Devonian age rocks Gunards Head, Cornwall

Table 4.15. Important igneous features, continued

Igneous feature	Description		Image	Source
Sill	Magmas intruding along sedimentary or volcanic layers (bedding planes) cool and crystallise, forming sills	Most sills and dykes are medium-grained and some have chilled (finer-grained) margins. Some metamor-phose the rocks they intrude, producing baked margins		The Whin sill at High Cup Nick in Cumbria. The dark-coloured sill has intruded flat-lying Carboniferous limestone
Dyke	Dykes form when magmas fill fractures in rocks, and then cool and crystallise			Pale granite dyke cutting through darker bedrock at Porthmeor in Cornwall
Pluton/ batholith	Batholiths were large magma chambers, plutons were smaller ones. When the magma cooled down slowly, coarse-grained igneous rocks like granite or gabbro formed. They usually baked the surrounding rock, forming a metamorphic aureole			Satellite image of the Bodmin Moor granite pluton in Cornwall; outcrop outlined in red

Igneous processes form part of the internal rock cycle, the part of the rock cycle driven by energy from the Earth. We have known how igneous rock cycle processes operated for many years, but their underlying causes have only been understood more recently, through plate tectonic theory, as in Table 4.21.

Box 4.7E. The Whin Sill – a dolerite sill underlying Hadrian's Wall



Hadrian's Wall was built by the Romans around 120CE. For part of its length it follows the top of the north-facing scarp slope of a cuesta formed by the dolerite igneous intrusion of the Great Whin Sill. The sill is roughly 70 metres thick and was intruded around 300Ma ago at the Carboniferous/Permian boundary. It dips gently to the south beneath overlying sedimentary rocks. The scarp face is very steep, with near-vertical joints in the dolerite.

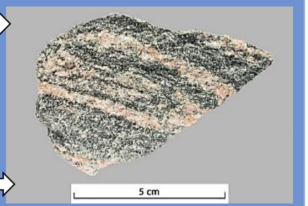
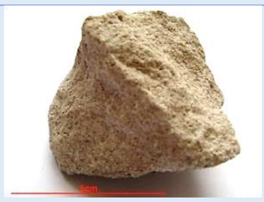
Elizabeth Devon

4.1.2.4 Metamorphic processes

Rocks are metamorphosed when tectonic plates collide in mountain-building episodes, with great underground increases in temperature and pressure; this process is called **regional metamorphism**. Rocks can also be metamorphosed through baking by nearby igneous magmas in **thermal metamorphism**. In both cases, the original sedimentary, igneous or other metamorphic rocks recrystallise in the solid state into metamorphic rocks. However, if the rocks become so heated that they melt completely, the change has gone beyond metamorphism to become an igneous process.

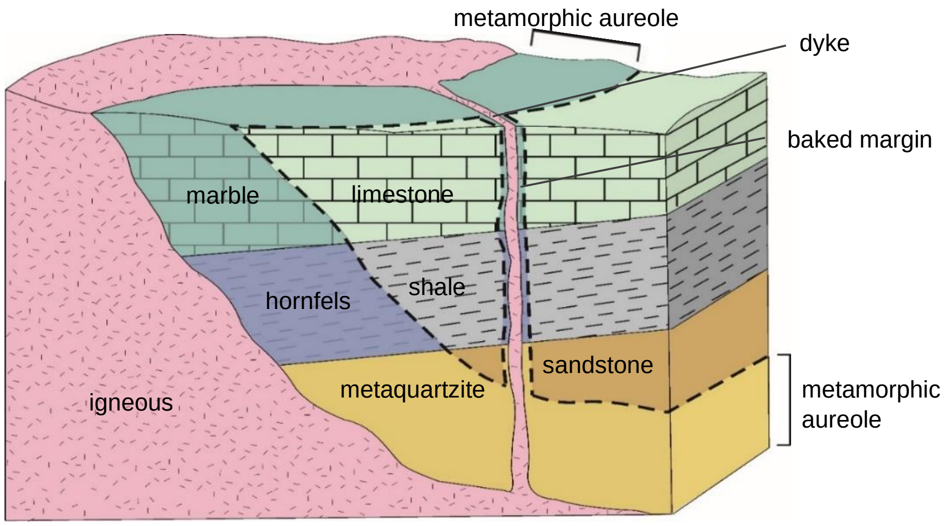
Regional metamorphism, caused by plate collision, produces rocks ranging from low-grade slates to high-grade gneisses, together with marbles and metaquartzites, as shown in Table 4.16. These resistant rocks are usually impermeable and tend to form higher land and fairly rugged landscapes.

Table 4.16. Metamorphic rocks formed by regional metamorphism

Original rock	Low-grade	Medium-grade	High-grade
 Mudstone	 Slate	 Schist	 Gneiss
 Granite			
 Sandstone		 Metaquartzite	
 Limestone		 Marble	

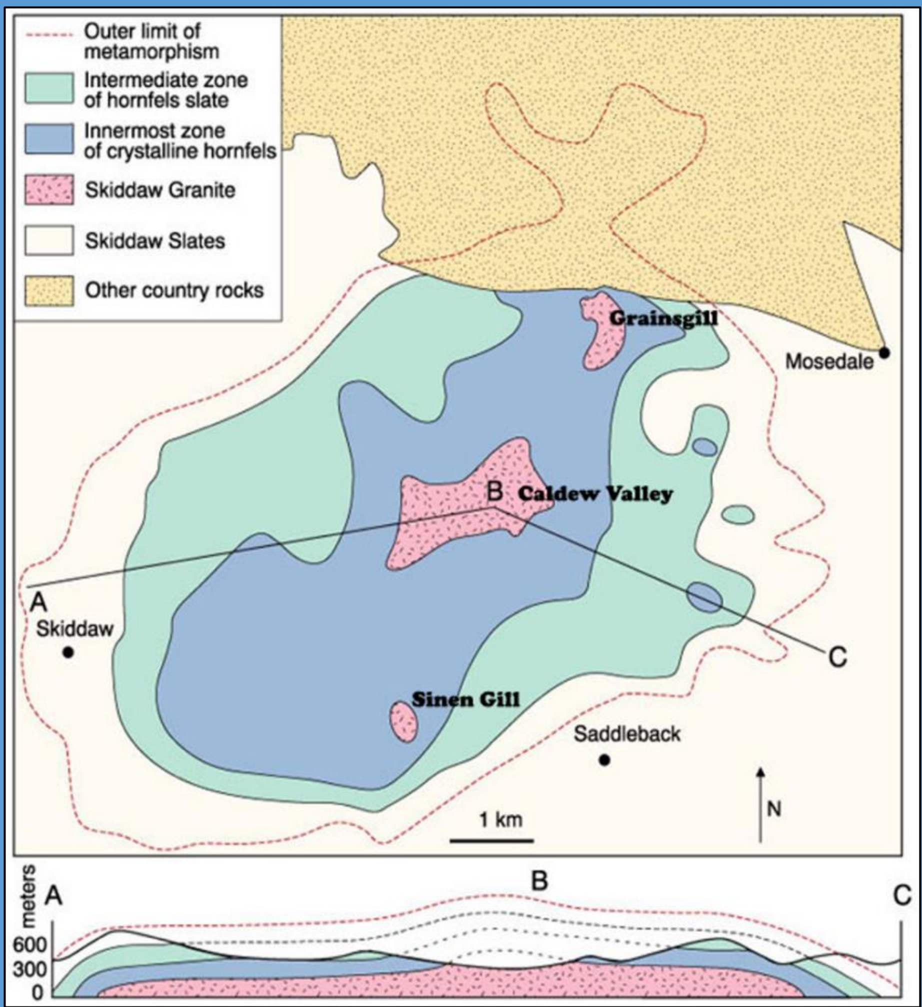
The amount of thermal metamorphism caused by igneous magmas depends on the size of the magma body. Small bodies simply bake the surrounding rock, producing narrow **baked margins**. Larger bodies contain a lot more heat energy and produce broad baked zones called **metamorphic aureoles**. Where fine-grained rocks are changed into hornfels, sandstones become metaquartzites and limestones become marbles (Figure 4.8 and Table 4.16).

Figure 4.8. Thermal metamorphic effects



The causes of the rock cycle process of metamorphism have now been explained by plate tectonic theory (Table 4.21).

Box 4.8E. The metamorphic aureole of the Skiddaw granite



Map and cross section of the Skiddaw granite metamorphic aureole, Cumbria

Box 4.8E. The metamorphic aureole of the Skiddaw granite, continued

The zone of thermal metamorphism around large igneous intrusions is called a metamorphic aureole. The Skiddaw metamorphic aureole was caused by the intrusion of the Skiddaw Granite around 400Ma ago. This granite intruded and baked Ordovician mudstones and siltstones which had previously been changed to slates by low grade regional metamorphism. The baking formed a concentrically-zoned aureole, roughly 1 km wide around the granite which caused the baking. The granite is exposed in three areas in the centre of the aureole.

A transect across the aureole from the south, shows a steady increase in the intensity of baking as metamorphic grade increases. Blue grey slates change into iron-stained rock with spectacular new crystals of the needle-like andalusite. Further towards the exposed contact with the granite, the mudstone becomes harder with spots of the mineral cordierite, forming a hornfels. This then becomes further altered to a crystalline hornfels containing the mineral sillimanite, as the granite is approached.

Slate with the new metamorphic mineral, andalusite

The thermal changes therefore result in a steady loss of previous rock structures, an increase in grain size and progressively higher temperature minerals as the granite is approached.

Pete Loader

Box 4.9E. A slate lithophone

In the Earthlearningidea activity, 'Rocks music', pupils are asked to make a musical instrument or lithophone, with a variety of rocks. From many experiments, it was discovered that slate was the best rock for the purpose. Rocks vibrate when hit. These vibrations generate mechanical waves of pressure which travel through the surrounding air, creating sound. The different resonant frequencies of the rocks give different notes. It was discovered that thin slates of different lengths produce a wide range of notes. See: https://www.earthlearningidea.com /PDF/308_Rocks_music.pdf

Elizabeth Devon

4.1.2.5 Deformation processes

When plates collide in mountain-building episodes, not only can rocks be metamorphosed, but they can also be deformed in different ways. At depths of below around 10 km, pressures and temperatures are so intense that most rocks bend and begin to flow to form **folds**. At higher levels, where there are still enormous lateral pressures, rocks tend to break rather than fold. So nearer the surface, rocks undergo brittle behaviour and fracture, whilst at greater depth they behave plastically, folding and flowing.

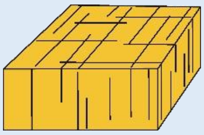
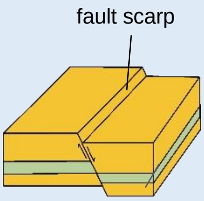
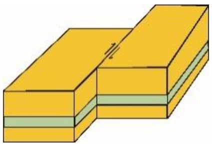
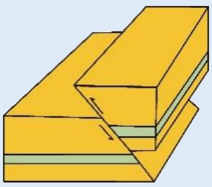
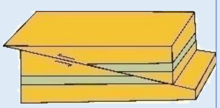
Rocks are also deformed when plates move apart or move past one another but, because temperatures are relatively low, they usually fracture rather than behaving plastically.

When rocks fracture, if there is no movement of the rocks on either side, a **joint** is formed. But if the rocks on either side are moved, the rocks are **faulted**. Many joints result from rocks being pulled apart, in tension. Tension, as rocks are pulled apart, also forms **normal faults**, when one side slides down relative to the other.

Where rocks slide past one another, **strike-slip faults** form, usually with near vertical faces.

Where rocks are being compressed, one side can be forced up and over the other in a **reverse fault** that has a faulted surface, or **fault plane**, of usually around 45º. Under very intensive compression, fault planes usually have lower angles of around 10º and these are called **thrust faults** (Table 4.17).

Table 4.17. Fractures caused by brittle failure – joints and faults

Feature	Stress	Description	Drawing	Image	Source
Joint sets	Horizontal tension	Set of parallel planes running through the rock with no relative movement, often vertical, sometimes horizontal or at other angles			Two sets of vertical joints cutting horizontal bedding in Jurassic limestone; Saltwick Nab near Whitby, North Yorkshire
Normal fault		Under tension, one block has slid down the fault plane relative to the other – usually steep, 60º or more			Normal fault of a coal seam in Carbon-iferous Coal Measures, Skelmers-dale, Lancashire
Strike-slip fault	Vertical sliding past	Blocks have slid past one another – usually on a near-vertical fault plane			Satellite view of the Piquiang Fault, Tian Shan Mountains, China
Reverse fault	Horizontal compression	Under compression, one block has been forced up over another – on fault planes of more than 45º			Reverse fault in volcanic ash, Borrowdale in Cumbria. (Lens cap 50mm)
Thrust fault		Under great compression one block has been forced over another – on a fault plane of less than 45º, often around 10º			Right hand block thrust up over left-hand block, Lilstock Bay, Somerset

Rocks that behave plastically when they are compressed form folds. Folds can have a range of sizes, from mountain to millimetre scale. Folds occur in series, as you can see by putting your hands on a cloth on a shiny surface and sliding them together. You will see a series of folds; the upfolds are called **anticlines** and the downfolds are **synclines**. The shapes of folds depend on the rock type and the amount of compression; they range in tightness from gentle **open folds** to **tight folds** to **isoclinal folds** with parallel sides. Folds can be angular or rounded. The area of bending of folds is the **hinge**, whilst the sides are the fold **limbs** (Table 4.18).

Table 4.18. Fold types

Fold type	Description	Image	Source
Anticline	Upfolded anticline – this anticline is a tight fold with a rounded hinge		An anticline in Carboniferous limestone, Apes Tor, Staffordshire
Syncline	Downfolded syncline – a tight fold with an angular hinge		A syncline in Carboniferous limestone, Apes Tor, Staffordshire
Open fold	An open fold, with an angle between the limbs of more than 45^{o}, and a rounded hinge		An open fold in Carboniferous limestone beneath the Whin Sill, Swine Den Northumberlan d

Table 4.18. Fold types, continued

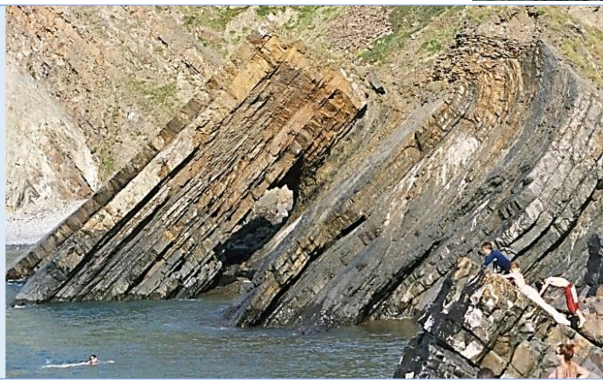
Fold type	Description		Image	Source
Tight fold	Tight folds have an angle of less than 45º	Tight folds with angular hinges		Tight folds with almost angular hinges in well-bedded Carboniferous limestone in the Clayton Mine, Ecton, Staffordshire
		Tight fold with a rounded hinge		Tight fold with rounded hinge in a thin dark limestone bed within black shale bands between pale Carboniferous limestone beds in the Clayton Mine, Ecton, Staffordshire
Isoclinal fold	Folds with parallel limbs			An isoclinal fold dipping down towards the left in Carboniferous sandstone, Hartland quay, Devon

Plate tectonic theory is now able to explain many of the underlying causes of Earth deformation, as explained in Table 4.21.

4.1.3 Structure of the Earth and evidence

We know what the rocks of the outer part of the Earth on the continents are like because we can see natural rock exposures in sea cliffs and mountain areas and can also see rocks in road and railway cuttings and quarries. We find out what the rocks are like deeper in the Earth through mines, and we also drill boreholes from metres to kilometres in depth. We know too what ocean floor rocks are like, because of the deep-sea drilling programme. But we must use other sorts of evidence to find out what the Earth is like below the depth of boreholes.

Box 4.5. The deepest borehole on Earth

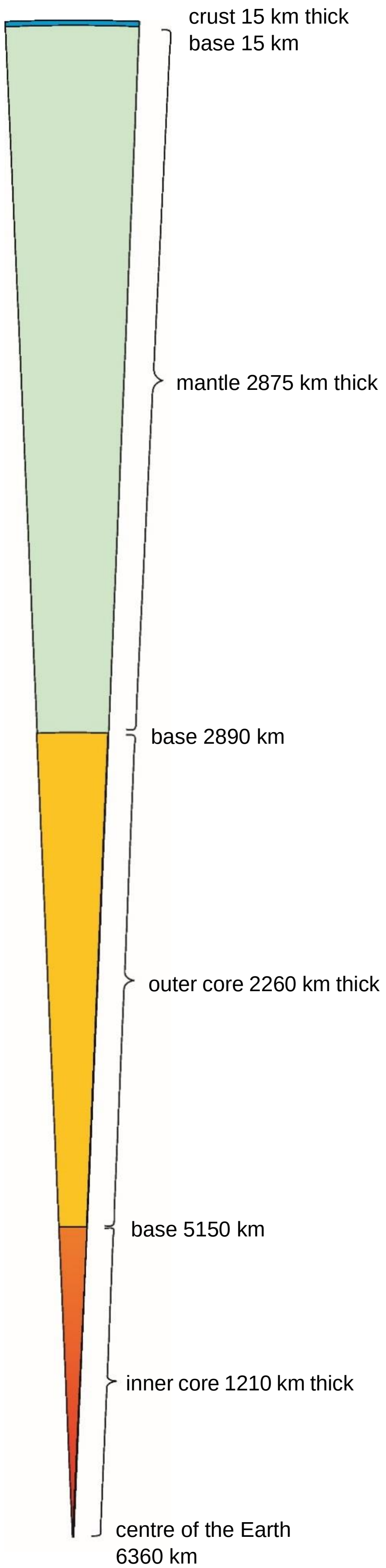
The deepest borehole ever drilled so far on Earth is the 12.3 km deep Kola Superdeep Borehole. This was drilled in the extreme north-west of Russia, taking more than 20 years and finishing in 1992. The borehole drilled around a third of the way through the continental crust, mostly through Precambrian granite and gneiss. One of the surprises was that the rock was still saturated with water deep in the borehole.

4.1.3.1 Evidence

The best evidence we have for what the Earth is like beneath our feet, below borehole depth, is the seismic evidence from earthquakes. Every time there is a large earthquake, shock waves travel right through the Earth as the whole Earth vibrates. They radiate through the Earth like ripples across a lake after you have thrown a stone in. The speed of the waves depends upon the material they pass through, and this helps us to work out where the boundaries between the different rock types are, and what the rocks are like.

We have other clues to the make-up of the layers of the Earth too, as described in the sections below, but it is the clues from seismic waves that have given us most information, shown in Figure 4.9.

Figure 4.9. Cross-section of the Earth

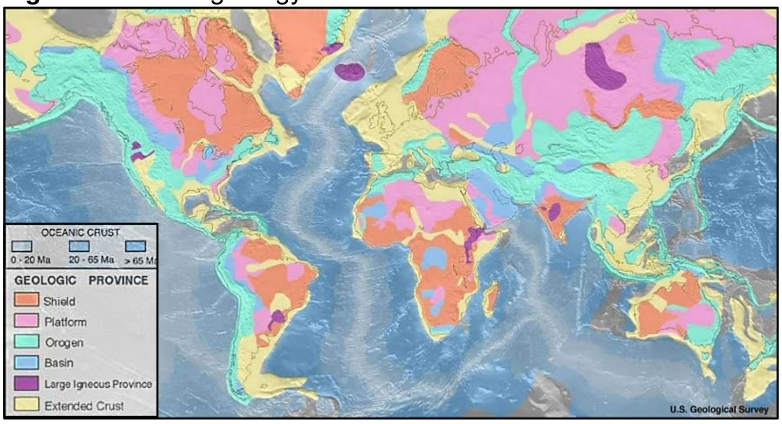


4.1.3.2 Crust

Figure 4.9 shows that the crust is very thin, when compared with the distance to the centre of the Earth. A good model of the crust's thickness is a postage stamp stuck onto a football. There are two sorts of crust: the continental crust found beneath continents and continental shelves, and the oceanic crust under the oceans.

The geological map in Figure 4.10 shows that the crust of the continents is much more complex than the crust of the oceans. This is because the continental crust is generally much older than the oceanic crust and some areas have been involved in several cycles of the rock cycle. The oldest rocks so far found on Earth are more than 4000 million years old, and form part of the continental crust in Australia. Meanwhile, the oldest parts of the oceanic crust are rarely more than 200 million years old and have a much simpler history.

Figure 4.10. The geology of the Earth's crust



The continental crust that we live on ranges in thickness from around 25 to 70 km. Although sedimentary rocks are only about 5% of the volume of the whole crust, they cover 75% of the continental crustal surface, about three-quarters of the brightly coloured area of Figure 4.10. Estimates suggest that these continental sedimentary rocks are about 79% mudstone, 13% sandstone and 8% limestone. Most of the volume of the continental crust is formed of igneous rock like granite, and metamorphic rock like gneiss (Figure 4.11). All these rocks have been formed by normal rock-cycle processes, even though some of the materials in them have been around the rock cycle several times.

The evidence for the structure and rocks of the oceanic crust includes seismic data, data from deep-sea drilling and information from places like Cyprus, where a plate collision has forced old oceanic crust up onto the continent. This evidence shows that oceanic crust has four main layers. On top is a layer of deep-sea sediments that are not found at ocean ridges, but become thicker and thicker moving away from the ridges. Beneath the sediments is a layer of fine-grained basalt, often in pillow lava form. The basalt overlies a layer made up of many vertical sheets of medium-grained dolerite dykes. Under that is a thick layer of coarse-grained gabbro, before the bottom of the oceanic crust and the top of the mantle are reached (Table 4.19).

Figure 4.11. The most common rocks of the continental crust

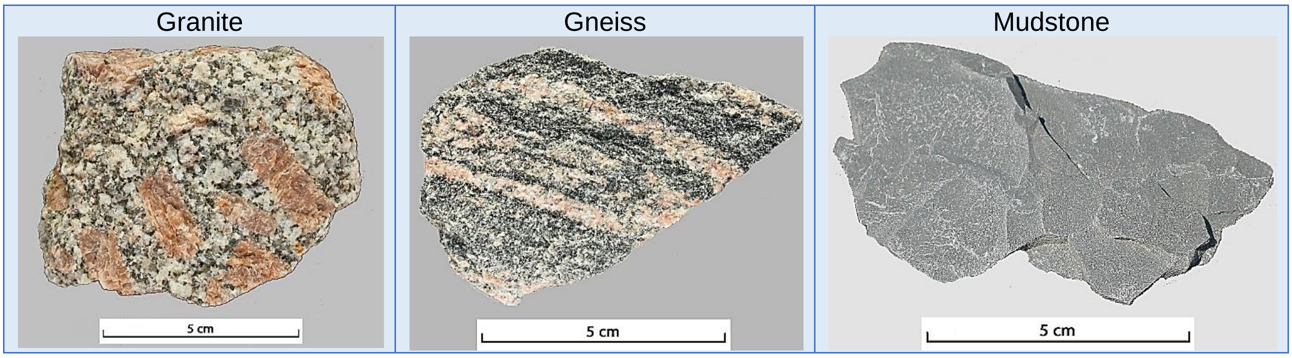
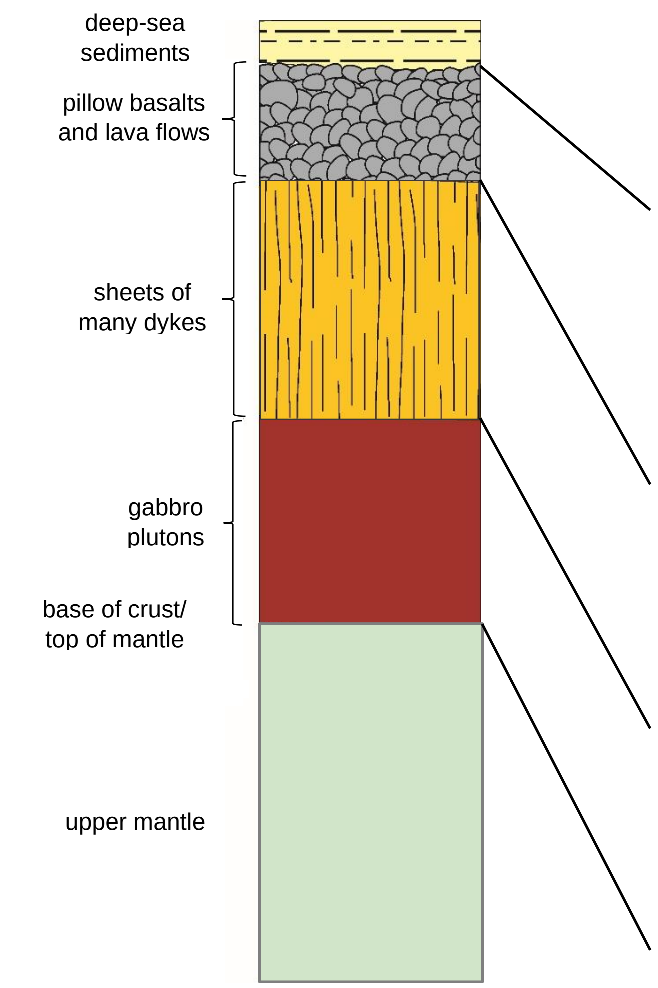
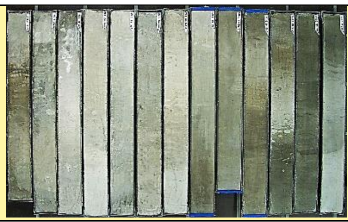


Table 4.19. Oceanic crustal rocks



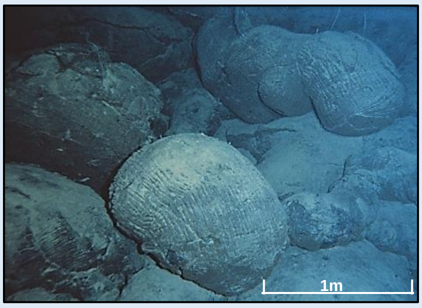
Deep-sea sediment – variable thickness 13m long core sample	
Basalt about 0.5 km thick	
Dolerite – about 1.5 km thick	
Gabbro – about 5 km thick	
Mantle rock	

The evidence shows how new oceanic crust is formed at divergent plate margins. Magma from local partial melting of the mantle rises at oceanic ridges. There it collects and solidifies below the surface, forming coarse-grained gabbro. If it rises through vertical fractures to the surface, it erupts as lava on the ocean floor, often with characteristic pillow lava shapes, and solidifies quickly into fine-grained basalt. Meanwhile the magma in the vertical fractures solidifies more slowly into medium-grained dolerite. Each time a fracture opens, a new sheet forms, producing more and more sheets of dolerite dykes.

Box 4.6. Underwater formation of pillow lavas

When basalt lava is erupted under water it forms ‘pillow shapes’. Tongues of orange or red-hot lava appear and their outer surface is quickly cooled by the water into a solid, but flexible, outer coating. As more lava is erupted, the newly forming rock becomes pillow-shaped. Later pillows squeezed out on top sag into the shapes of earlier formed pillows below. Since this process only happens in water, ancient pillows preserved in rock sequences show that they must have formed under water. Filming pillow lava formation can be very dangerous since the surrounding sea has invisible pockets of scaldingly hot water.


A tongue of lava underwater



Pillows on the sea floor near Hawaii


Ancient pillow lavas, cross-section

The newly formed three-layered oceanic crust is slowly moved away from the divergent plate margin by plate movement. Fine-grained mud (often the lime-rich shells of microscopic plankton) rains down from the ocean above and settles on top of the pillows. The further the plate travels, the thicker this sediment blanket becomes, until it may become 1 km or more thick near the edges of oceans.

At ocean margins, oceanic crust is often carried back down into the mantle again, through subduction. This explains why oceanic crust is usually no more than 200 million years old and why, the further away from the divergent plate margin the oceanic crust is, the older it becomes, as shown in Figure 4.10.

The mean density of the oceanic crust, as shown by the speed of earthquake waves and measurements of rock specimens, is greater than the mean density of the continental crust. The mantle underlies the whole crust, and many observations have shown that, although the mantle is completely solid, it is able to flow very slowly under the intense pressures and temperatures at depth and with the great amounts of time available (moving at around 1cm per year). So both the oceanic and continental crusts are supported by the underlying flowing solid mantle. It is because the oceanic crust is denser than the continental crust that it sinks to a lower level. This means that nearly all the oceanic crust is well below sea level, whilst most of the continental crustal surface is above sea level. The oceanic crust is also thinner, averaging only around 7 km in thickness (Table 4.20).

Table 4.20. Characteristics of the Earth layers

Layer		Mean depth, km		Mean thickness, km		State		Mean relative density*	
Continental crust	Oceanic crust	35	7	35	7	Solid	Solid	2.7	2.9
Mantle		2890		2875		Solid		3.3 – 5.7	
Outer core		5150		2260		Liquid		9.9 – 12.2	
Inner core		6360 Earth centre		1210		Solid		12.6 – 13.0	

* Relative density is the ratio of the density of a material to the density of water – and so needs no units

4.1.3.3 Mantle

The boundary between the crust and the underlying mantle was discovered from earthquake wave measurements in 1909. Modern seismic data provide evidence that much of the solid mantle can flow over geological time, accounting not only for the ‘floating’ of the crust but also the movement of the Earth’s tectonic plates.

Box 4.7. What is the mantle made of?

An attempt to drill through the ocean crust to the mantle in the 1960s failed, so the only evidence we have for what mantle rocks might be like is second-hand evidence.

5 cm

Some volcanic eruptions contain fragments of other rock that are thought to have been brought up from the mantle beneath

5 cm

In some mountain-building collision zones, mantle rocks seem to have been pushed up onto the continent, with ancient oceanic crustal rocks on top

5 cm

Stony meteorites are thought to have come from the mantles of small planets that disintegrated in the past

Based on this and other evidence, the mantle is thought to be made of peridotite and similar rocks. Peridotite is a very dense rock formed mainly of the minerals green olivine and dark-coloured pyroxene.

4.1.3.4 Core

The relative density of the whole Earth is around 5.5 but the density of the outer parts of the Earth is much less than this; therefore, the Earth must have a much denser core. The boundary of the core was discovered from seismic studies in 1914. Further seismic data showed that the outer part of the core is liquid (since seismic shear waves will not travel through) whilst the inner part of the core is solid. Currents in the liquid outer core are thought to generate the magnetic field of the Earth.

Box 4.8. What is the core made of?

The boundary of the core is nearly 3000 km below the Earth's surface, so we will never be able to sample core rocks. We therefore need second-hand evidence to work out what the core is likely to be formed from. Iron has the right density to be a core rock and is a commonly found material in space. Many meteorites are iron meteorites made of a blend of iron with a little nickel; these are thought to have come from small planets that broke up in the ancient past. This blend of iron and nickel has similar density and seismic characteristics to the core. So the core is thought to be made of an iron-nickel alloy. It is liquid in the outer core and solid in the centre. Recent research suggests that the core may contain a little silicon as well.

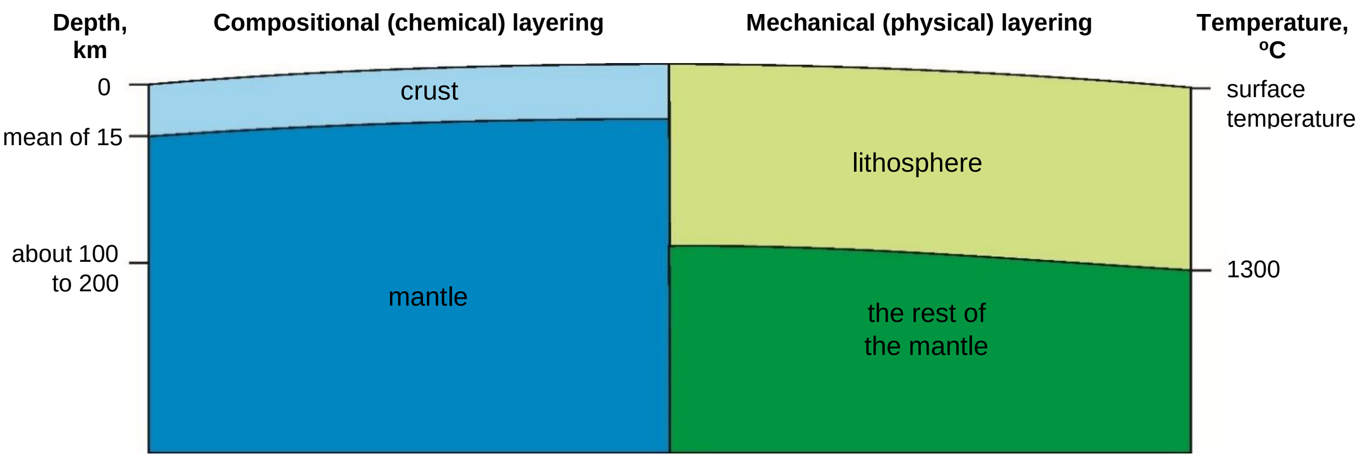
An iron meteorite 30 cm across from Siberia – the outer part melted as it fell through the atmosphere

4.1.3.5 Lithosphere

The crust-mantle and mantle-core boundaries are marked by changes in chemistry; the crust is rich in silicon with some iron, the mantle contains a lot more iron, and the core is almost entirely iron. We now know that there is another important boundary in the Earth, marked not by chemical changes but by mechanical changes, changes in the way the rocks behave.

The boundary is the base of the lithosphere, marked by the zone where the temperature of the rock reaches around 1300ºC. The rocks above that temperature zone are solid and rigid, whereas below that zone they are solid but able to deform and flow very slowly. The solid and rigid lithosphere is made of the crust and the extreme upper mantle, and forms the Earth's plates. These are moved by plate tectonic processes, with the weaker mantle beneath allowing that movement. Figure 4.12 shows the structure of the outer Earth with the crust, lithosphere and mantle.

Figure 4.12. The outer part of the Earth

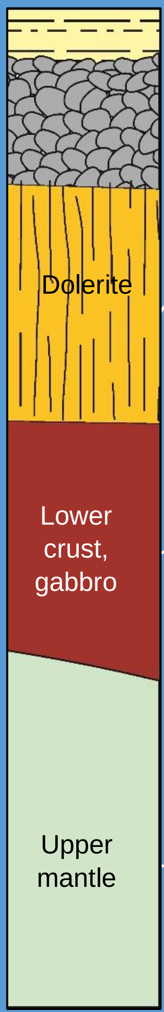


The Earth's plates are therefore made of lithosphere and are able to move on the rest of the mantle. Although the mantle is solid, it can flow slowly. Plate properties and movement are described by the theory of plate tectonics.

Box 4.10E. Walking over an oceanic plate in Cornwall

The Lizard is the southern tip of Cornwall and the rocks found there are called the Lizard Complex because they are a mixture of a variety of rocks. These include examples of serpentinite (a rock formed when mantle rock is altered by hot fluids), gabbro, sheeted dolerite dykes and pillow basalts. However, the links between these rocks are not clear because of the faulting there.

For many years, geologists found these rocks confusing, but they have now realised that these are part of an ancient oceanic plate forced upwards by large thrust faults. The rocks are part of an ophiolite complex formed when plate convergence forced up slices of oceanic rocks as part of a mountain-building episode. It is the faulting which has made the Lizard Complex so complicated and difficult to understand. But it is one of the few places on Earth where you can walk from the mantle to the oceanic crust on land.



Sheeted dolerite dykes on the Lizard, Cornwall

Layered gabbro cumulate rocks, Coverack

Serpentinite cliff, altered mantle rock, Kynance Cove, Lizard, Cornwall

Chris King

4.1.4 Plate tectonics and evidence

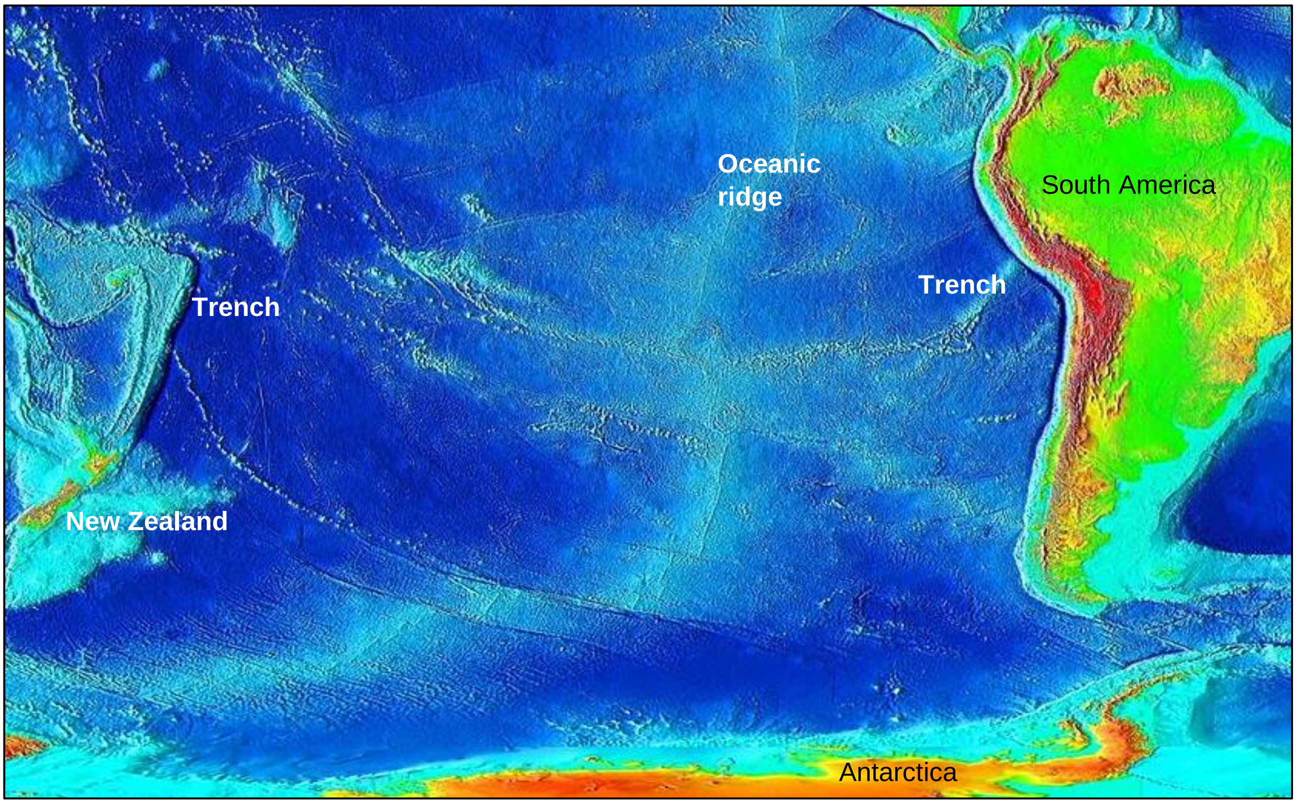
4.1.4.1 Unifying theory

As soon as reasonably accurate world maps became available, it was noticed that the coastlines of Africa and South America showed a close match with each other. But it wasn't until 1915 that Alfred Wegener published a book with evidence showing that they had once been together, his **Continental Drift** theory. The book, which was published in English in 1922, included evidence, not only for the jig-saw puzzle fit of the continents, but also for the matching geology and the fossils on either side. Wegener also showed how continental drift could explain the changing environments recorded in continental rocks, where ice deposits were often followed by desert sandstones and later equatorial rocks. His work was largely ignored, partly because he could not suggest a convincing mechanism to move the continents. Most geologists at the time thought that the Earth's crust could move up and down but not sideways. It was also thought that the Earth's crust was too thin to form drifting continents. We now know that the Earth's crust really is too thin to form plates; plates are formed of the much thicker lithosphere (Figure 4.12).

During the Second World War in the 1940s, scientists developed two methods for detecting underwater submarines that later were critical to the plate tectonics story. The sonar method fires sound waves through the water and receives any that bounce back; this can detect submarines but also the sea floor and its depth. Magnetometers were also developed to detect the magnetism of submarines, but were also later used to detect magnetic changes in the ocean floor.

In the 1950s and '60s sonar was used to map the floors of the oceans. The mapping showed that the oceans had shallower ridges near the centres of oceans and deeper areas, called trenches, near the ocean margins. Some of the ridges were more than 1.5 km high and the trenches went down to depths of more than 11 km (Figure 4.13). This led Harry Hess to propose his **Sea Floor Spreading** hypothesis in 1962. Hess proposed that new ocean crust was being formed at the ridges near the centres of oceans, and was being moved sideways until it reached the trenches, where it was taken back into the mantle. Temperature played a key role in his theory. Where new material was being formed, it was very hot and so of lower density, producing the ridges. As the material was moved away, it cooled and sank until, at the trenches, it became so cold and dense that it could sink back into the mantle.

Figure 4.13. The southern Pacific Ocean floor; oceanic ridge near the centre and trenches to East and West



While scientists were mapping the ocean floor using sonar, they also used magnetometers to measure ocean floor magnetism. They found that the ocean floor was magnetic. In some places, the magnetism aligned with the normal magnetism of the Earth, to give a stronger magnetic signal. In other places, the ocean floor magnetism was in the opposite direction and cancelled out some of the normal Earth magnetism to give a weaker signal.

When all this was plotted on a map, a pattern was seen either side of the oceanic ridges, like the one shown in Figure 4.14. This was explained by Vine and Matthews in the UK and by Morley in Canada in 1963. They already knew that, when rocks containing magnetic minerals cool down, they become magnetised in the same direction as the magnetic field in which they cool. So basalt lavas cooling down today become magnetised in the direction of today's magnetic field, with a north-south magnetisation. They also knew of the theory that although the north magnetic pole is currently near the geographical North Pole (and the south magnetic pole near the South Pole), this magnetism has flipped many times in the geological past. There had been times, therefore, when the north magnetic pole was near the South Pole and the south magnetic pole near the North Pole.

This helped them to explain that the magnetic pattern on the ocean floor was formed by basalts that had become magnetised as they cooled. If they cooled when the Earth's magnetism was in the same direction as today's, they took on a north-south magnetism, but if they cooled when it was in the opposite direction, they took on a south-north magnetism. Rocks with north-south magnetism reinforce today's north-south magnetism giving a positive anomaly, called **normal magnetic polarity**. Basalts with south-north magnetism reduce the overall magnetic field, giving a negative anomaly, called **reversed magnetic polarity**, as in Figure 4.15.

Figure 4.14. Magnetic anomalies over the Reykjanes Ridge south-west of Iceland

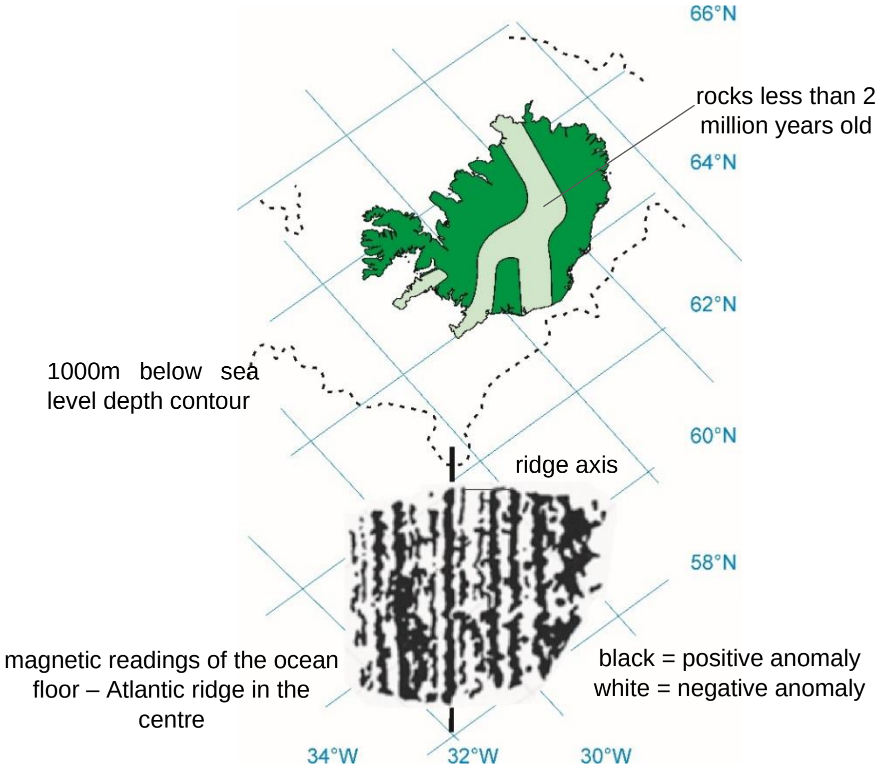
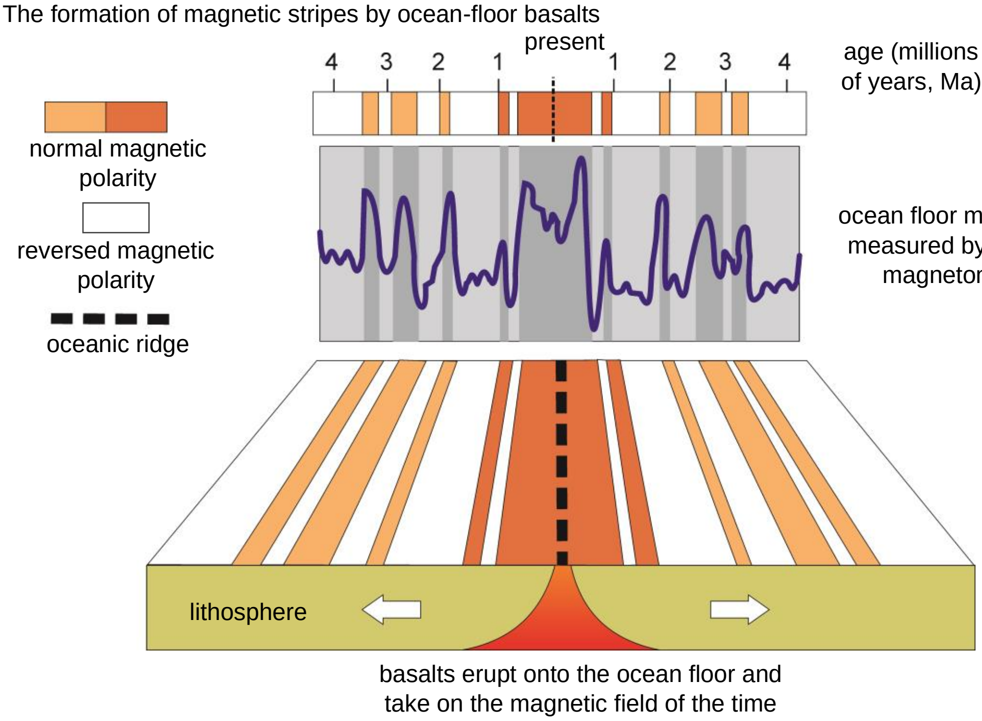


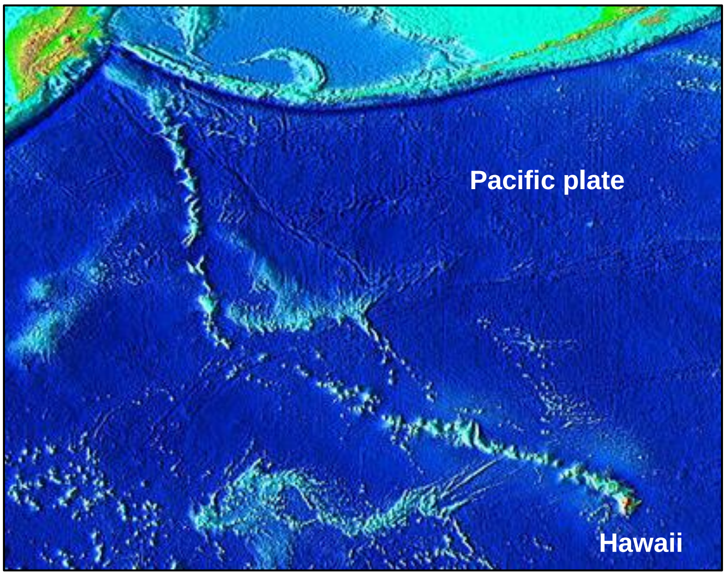
Figure 4.15. The formation of magnetic stripes by ocean-floor basalts



Reversals of Earth's magnetic poles are not regular: sometimes there can be a long interval between reversals and at other times they happen quickly. This is why ocean floor magnetic stripes have different widths, and also why the pattern on one side of an oceanic ridge is the mirror image of the pattern on the other side. The magnetic stripe evidence provided excellent support for Hess's Sea Floor Spreading hypothesis.

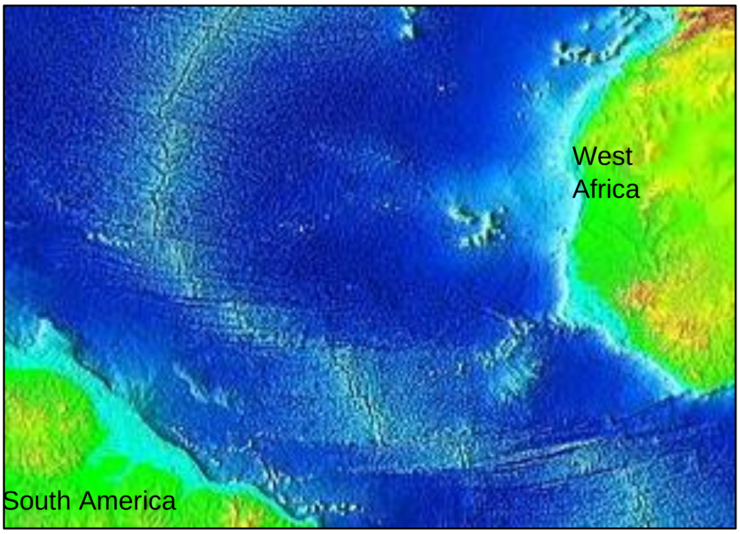
One of the problems with the sea floor spreading idea was that volcanic activity in the oceans was not only centred on oceanic ridges, but was also found in some volcanic islands far from ridges. John Tuzo Wilson explained this in 1963 through his hotspot theory. A hot plume of rock rises in the mantle and partially melts to form basalt magma. This rises through the lithosphere to erupt through a volcano. As the lithosphere is moved over this hotspot, a chain of volcanoes is produced, as shown in Figure 4.16. The further away from the hotspot the volcanic islands have been carried, the older they are.

Figure 4.16. The chain of volcanic islands and undersea volcanic seamounts linked to the Hawaii hotspot in the Pacific Ocean. The sudden bend in the chain is linked to a change in the direction of movement of the Pacific plate



In 1964 John Tuzo Wilson recognised another key piece of evidence supporting the sea floor spreading idea. He realised that not only was new sea floor being formed at oceanic ridges and taken back into the mantle at oceanic trenches, but also that the oceanic ridges were offset in many places by huge faults, that he called **transform faults** (Figure 4.17).

Figure 4.17. Transform faults offsetting the Atlantic Ocean oceanic ridge



All this evidence together became the new unifying theory of plate tectonics, that was widely accepted in the mid-1960s. The new theory unified Wegener's Continental Drift theory with Hess's Sea Floor Spreading theory and all the other evidence to explain that the whole outer Earth was broken into pieces, later called plates, that moved across the Earth's surface. These plates had three sorts of margins: the oceanic ridges and trenches recognised by Hess and the transform faults recognised by Wilson. As plates moved, they carried the continents with them, so the continents did not drift, as proposed by Wegner, but were carried by plate movement.

Wilson then realised that plate movement could account for the formation of supercontinents in the geological past, and that, as continents were moved together, and then were later broken apart, new oceans were formed. This cycle of supercontinent formation and break-up is now called the **Wilson Cycle** or the **supercontinent cycle**.

The new unifying theory not only explained global-scale geological features, but also accounted for the mountain-building episodes and uplift that are key parts of the rock cycle. It explained how areas could have rock sequences where the sedimentary rocks had been laid down in very different environments, that could range from glacial to equatorial and from deep seas to mountains. Plate movement was later seen as one of the driving forces behind evolution as well – so unifying many areas of geology. Since then, more and more evidence has been found supporting plate tectonic theory; it explains most but not all geological features. It is those features that are not explained by 'normal' plate tectonic theory that are the focus of much scientific research today.

4.1.4.2 Plate construction and subduction

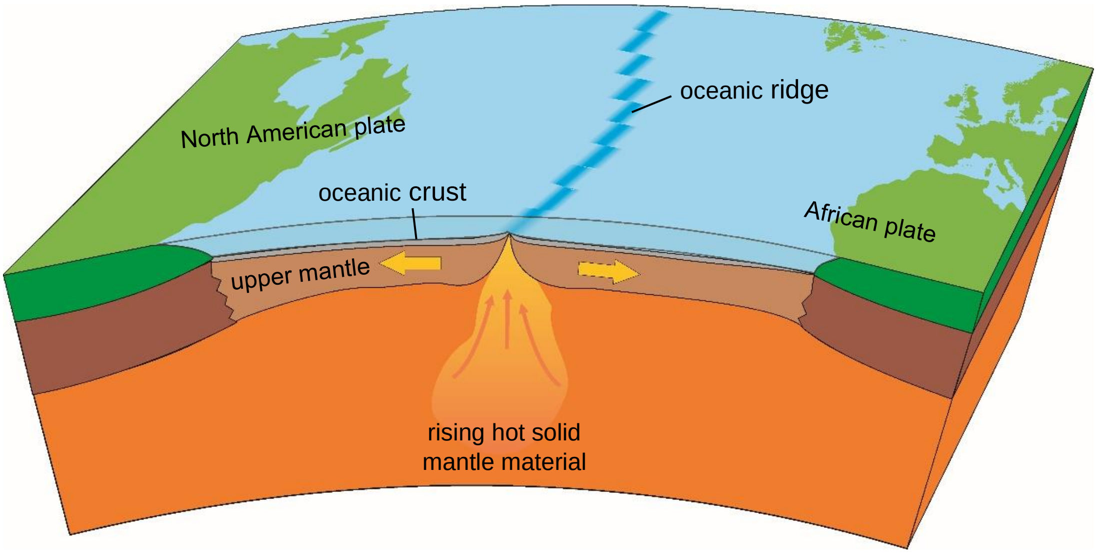
The Earth's lithosphere is broken up into a series of large and small pieces called tectonic plates. As these plates move, they carry the continents with them. At oceanic ridges, new plate material is formed and is moved away from the ridge, so these are called **divergent plate margins**. Oceanic ridges are offset by transform faults where no plate material is constructed or lost, so these transform faults are also called **conservative plate margins**, where plate is conserved.

The new warm and buoyant plate material of oceanic ridges slowly cools and sinks as it moves away from the ridges. Eventually it becomes so cold and dense that it begins sinking back into the mantle; this sinking is called **subduction**. The result of subduction is that two plates move towards each other, which is why they are also called **convergent margins**. The subducted lithosphere becomes incorporated back into the mantle so that the rocks of the lithosphere become recycled through the global plate tectonic cycle.

4.1.4.3 Characteristics of plate margins

Divergent plate margins. At these margins, new plate material is formed at oceanic ridges as the plates are pulled apart, allowing magma formed by the partial melting of the mantle beneath to rise. This solidifies in magma chambers producing gabbros, in dykes as dolerite, or on the ocean floor as the basaltic lavas in Table 4.19. This new crust, together with part of the mantle beneath, becomes new lithosphere as new oceanic plate is created (Figure 4.18).

Figure 4.18. New oceanic lithosphere being created at the oceanic ridge in the mid-Atlantic Ocean

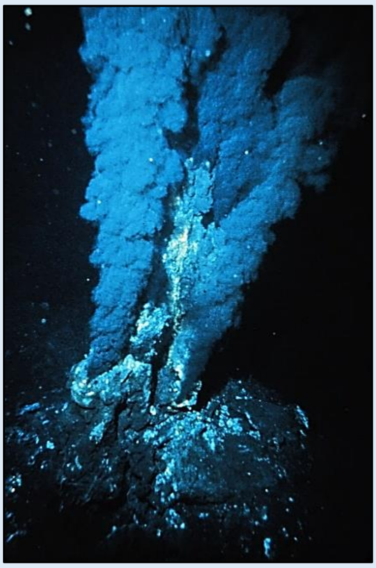


Box 4.9. The discovery of black smokers at oceanic ridges

In 1977 the deep-sea submersible submarine *Alvin* was investigating an oceanic ridge area 2 km deep, when its two pilots saw black smokers for the first time. They discovered that the black smoky water bubbling out was superheated to more than 400ºC and strongly acidic. They found strange life forms living off the energy and nutrients produced by the smokers. Further investigation showed that cold seawater was being pulled down into the cracked sea floor nearby, where the hot rocks beneath heated it up. The superheated water dissolved minerals from the surrounding rocks as it rose back to the sea floor. When it bubbled out, the water reacted with the seawater and black minerals crystallised out as 'black smoke'. These are now called **hydrothermal vents**.

This amazing discovery, of a new unimagined process deep on the sea floor, changed our understanding, not only of chemical oceanic processes, but also of how biological communities could develop without light. It also gave new insights into oceanic ridge geophysics. It is unusual for one discovery to have such an impact on our understanding of biology, chemistry and physics. *Alvin* and other deep-sea submarines are still following up this discovery today. White smokers have now been discovered on ocean floors away from oceanic ridges, with bubbling alkaline white 'smoke' of pale-coloured minerals in liquid carbon dioxide.


Deep-sea submersible vehicle, Alvin


Black smoker, Atlantic ridge


White smokers, Mariana Arc, Pacific Ocean

As newly formed plates are pulled apart, this causes tension and rifting as the solid plate is fractured by a series of normal faults. The central part slides down into a rift valley. Such rift valleys are found at the centre of oceanic ridges across the world (Figure 4.19). Iceland is one of the few places where an oceanic ridge is found on land; Figure 4.20 shows a small Icelandic rift valley forming part of the larger oceanic ridge rift system.

Figure 4.19. The rift valley at the centre of an oceanic ridge

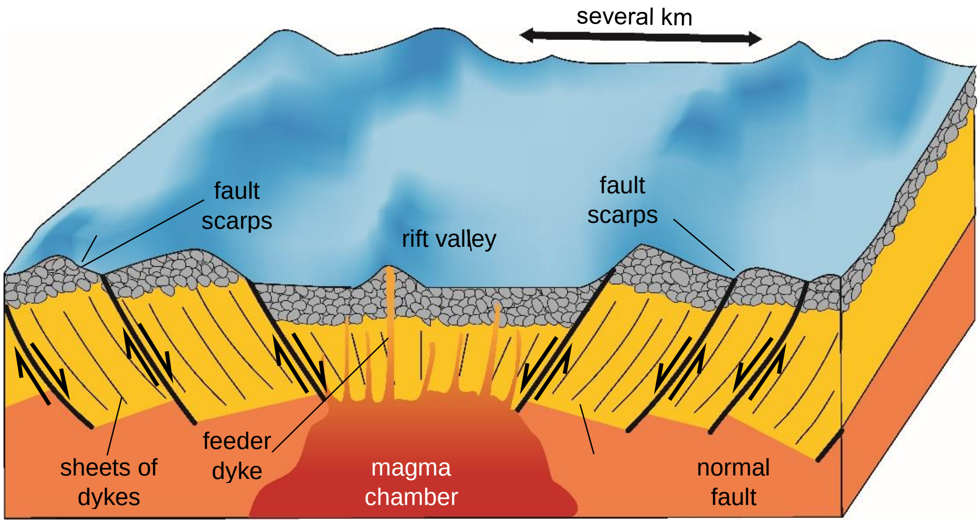
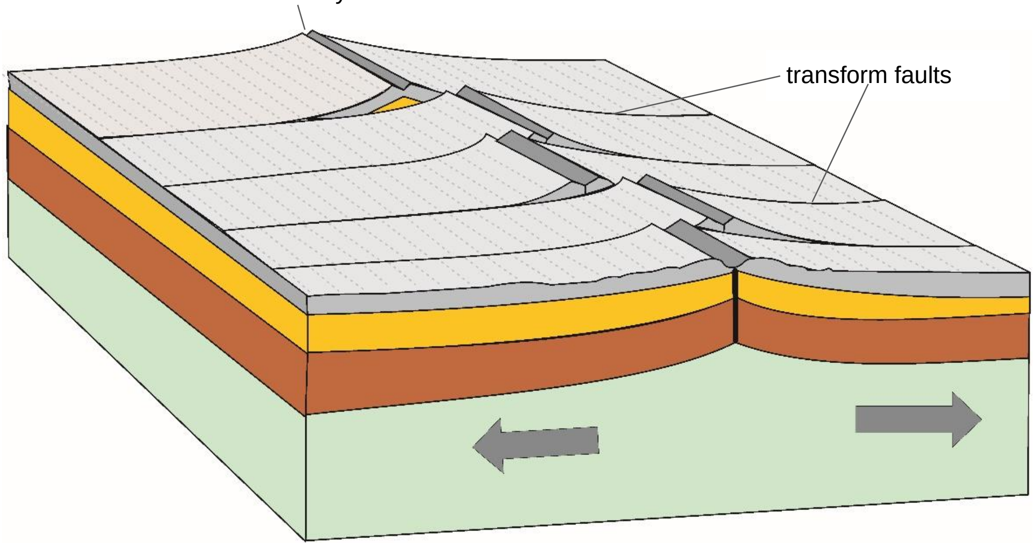


Figure 4.20. A small rift valley in Iceland, linked to oceanic ridge rifting

Recent deep-sea drilling and seismic evidence show that new oceanic lithosphere is being formed in a different way in some parts of the ocean. In some areas, it seems that slabs of mantle are being pulled bodily up from beneath, along deep faults, to become new oceanic lithosphere. This newly recognised process is still being investigated. However the new oceanic lithosphere is being formed, as soon as it appears, deep-sea muds begin settling on top from the ocean above. This blanket of mud becomes thicker and thicker as the plate is moved away from the oceanic ridges and across the deep ocean floor.

Conservative plate margins. Oceanic ridges are offset by transform faults (Figure 4.17) at these margins and these are unlike any other faults. Although they move past each other in ordinary strike-slip movement, they extend into fracture zones beyond the oceanic ridges, where the rocks on each side of the fault move in the *same* direction, although at slightly different speeds, as in Figure 4.21.

Figure 4.21. A series of transform faults offsetting an oceanic ridge and rift valley

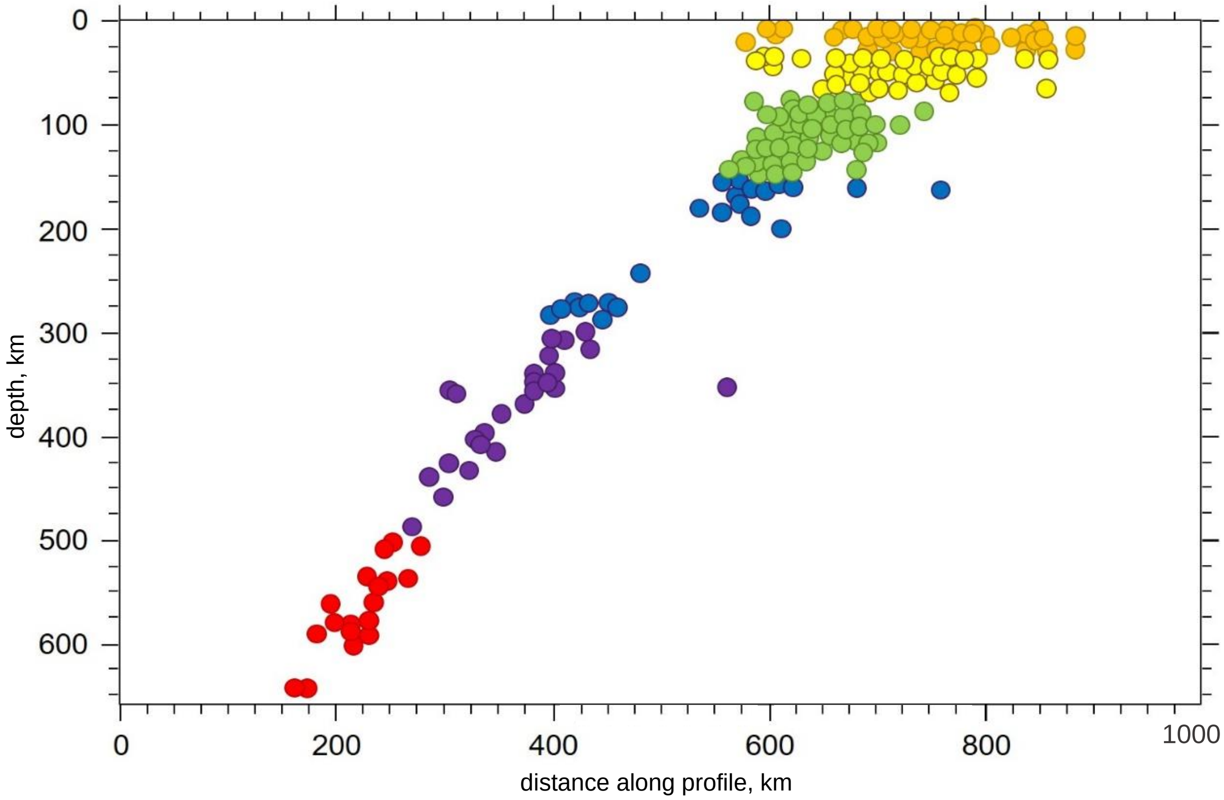


Transform faults not only offset oceanic ridges but also link oceanic ridge margins with subduction zones. They affect continents too; famous examples cutting continents are the Alpine Fault in New Zealand and the San Andreas Fault in the USA (Figure 4.22). As transform faults are conservative plate margins, they have no volcanic activity, despite what might be shown in some popular movies.

Figure 4.22. The San Andreas Fault in California, USA. The ground in the foreground has been faulted 130 metres to the left since the stream first cut its valley, offsetting it by this distance

Earthquakes occur at all active plate margins but, when compared with those at subduction zones, the earthquakes at divergent margins and transform faults are all shallow focus; they only occur to the depth of the lithosphere, which is less than 100 km thick. However, where plates are being subducted, cold lithosphere is being carried down into the mantle and can cause earthquakes at all depths down to around 750 km. The subduction causes a sloping zone of earthquakes, seen in Figure 4.23.

Figure 4.23. Earthquakes recorded across the Kurile Islands subduction zone in the north-west Pacific Ocean. The earthquakes are colour-coded for depth, showing that the plate is being subducted to the left



As the cold oceanic lithosphere sinks into the mantle, it carries seawater trapped in the rocks with it. This water, together with the increase in temperature as the lithosphere sinks, causes the rocks above the subducting lithosphere to partially melt, producing magma. Once formed, the hot magma has a lower density than the rocks above and rises, causing igneous activity in the plate above.

The effects of subduction are different depending on where the subduction occurs. Where one oceanic plate subducts beneath another, a series of volcanic islands is produced. Where an oceanic plate subducts beneath a plate carrying a continent, a mountain range is formed with associated volcanic activity. Where two plates carrying continents are brought together by subduction of the oceanic lithosphere in between, an even larger mountain range results from the collision.

Ocean-ocean convergent margins. When two oceanic plates are being moved towards one another, the cooler plate is denser and so subducts. Subduction produces a deep-sea trench where the two plates meet and a sloping zone of earthquakes, as in Figure 4.23. Partial melting of part of the subducting slab produces intermediate magma (neither iron nor silicon-rich) which rises in explosive volcanic eruptions producing a chain of volcanoes. The trench and volcanoes form a curve across the Earth's surface giving another name to this type of margin: an **Island Arc** margin (Figure 4.24).

Figure 4.24. Subduction at a collision of two oceanic plates

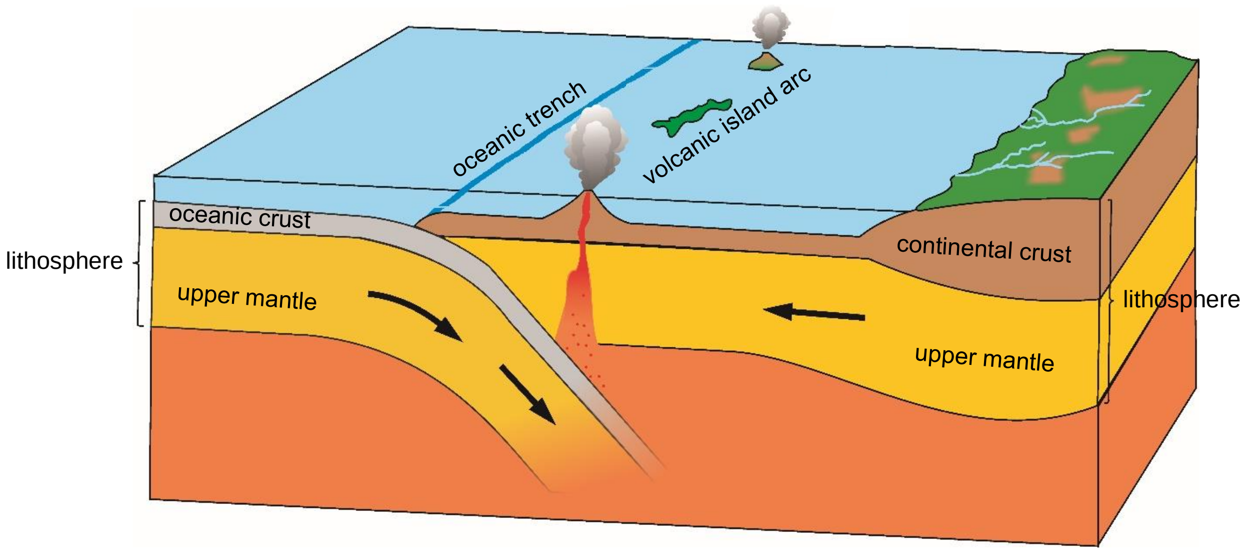


Figure 4.25. The Caribbean island arc, showing the curve of the deep-sea trench with the arc of volcanic islands inside, as the North Atlantic plate collides with the Caribbean plate

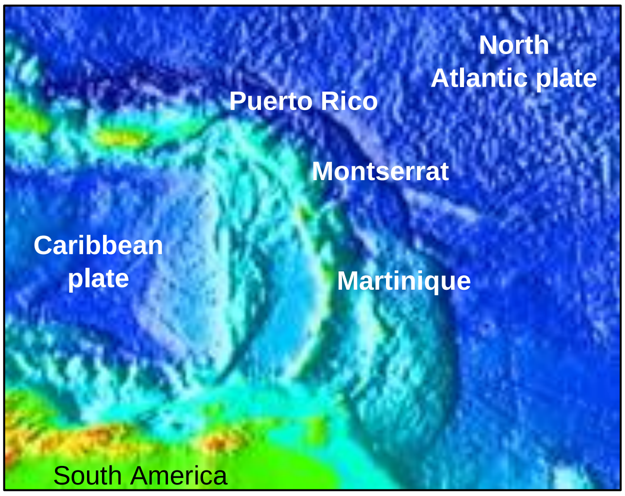


Figure 4.26. Soufrière Hills volcano erupting on Montserrat Island in the Caribbean island arc

Ocean-continent convergent margins. When an oceanic plate collides with a plate carrying a continent, the continental rocks are less dense than the oceanic lithosphere, causing the oceanic plate to subduct. As with island arcs, a sloping zone of earthquakes results, coupled with explosive volcanic eruptions. However, because there is a continent on one plate, there are many other effects as well. As the oceanic plate is subducted, slices of the ocean floor are forced off and piled up, as shown in Figure 4.27, into a thick wedge of sediments called an **accretionary prism**. This adds new material to the continent, so that it grows outwards. It also grows upwards and downwards too because, as new material is added, mountains are formed and it becomes thicker. As the mountains become higher, they sink further into the mantle beneath, because the mantle, although solid, is able to flow. So, as the mountains of the continental crust become higher, their bases are forced to lower depths. The masses of continental crust forced down to support mountain chains are called **mountain roots**.

Although the temperatures and pressures of mountain roots are intense because of their great depth, there are extra compressional pressures too caused by the force of the plates moving together. It is these lateral pressures that deform and metamorphose rocks. Meanwhile, magma is produced by the partial melting linked to the subducting plate. Not only are intermediate magmas produced, but partial melting of the lower crust produces silicon-rich melts as well. These are mostly so viscous that they solidify before they reach the surface in large magma chambers, forming plutons and batholiths. The slow cooling of this silicon-rich rock forms granite. If silicon-rich magma does reach the surface, like intermediate magma, it causes highly dangerous explosive eruptions of volcanic ash.

Figure 4.27. Subduction of an oceanic plate beneath a continental plate

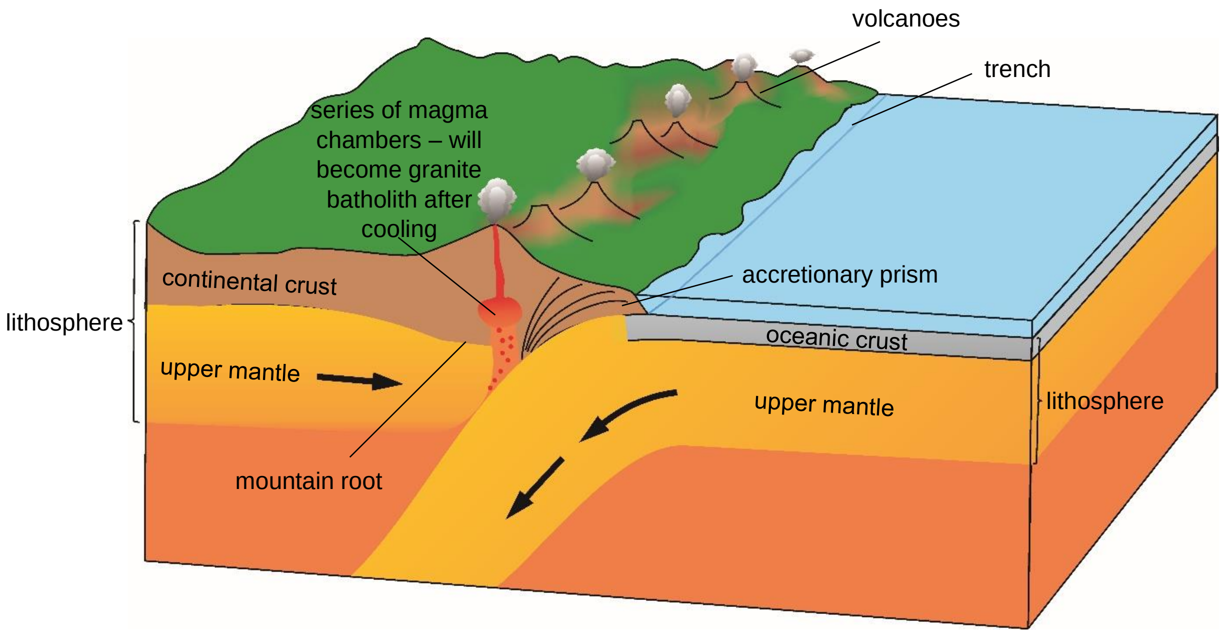


Figure 4.28. The collision zone formed by the Nazca plate subducting beneath the South American plate

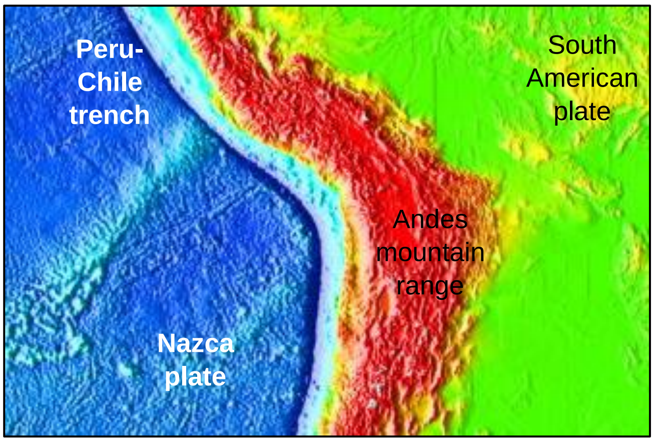


Figure 4.29. The Andes mountain range between Chile and Argentina

Continent-continent convergent margins. As two plates carrying continents are moved towards one another, the oceanic plate between subducts and the ocean gradually closes. As the continents on the plates collide, high mountain ranges with deep roots are produced, the highest mountain ranges on Earth. The collision causes intense deformation, with large-scale thrust faulting and folding, together with metamorphism up to the highest grades. Although the collision zone can be active for millions of years, no more subduction can take place so there is no volcanic activity. Nevertheless, the region is very prone to earthquakes, often of high magnitude and catastrophic (Figures 4.30, 4.31 and 4.32).

Figure 4.30. A collision zone between two continental plates

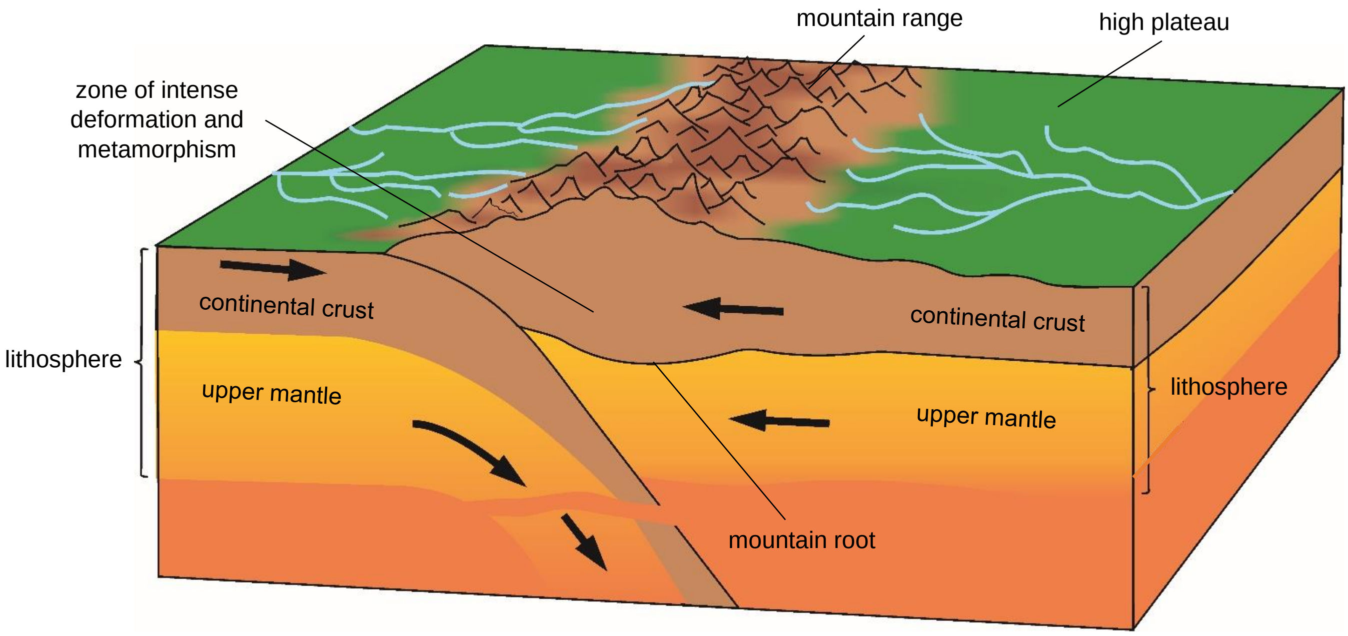


Figure 4.31. Collision of the Indian plate with the Eurasian plate, producing the Himalayan mountain chain

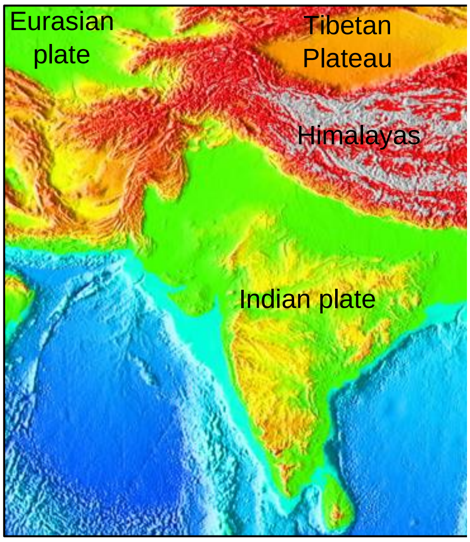
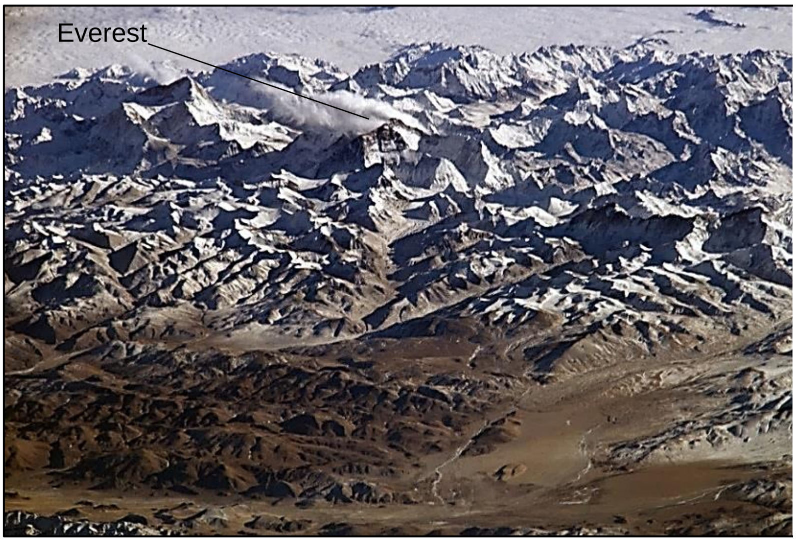


Figure 4.32. The Himalayan mountain chain seen from the International Space Station, with Mount Everest at the centre top



Box 4.10. Thrust sheets produced by plate collisions

When two continental plates collide, sheets of rock can be thrust up and may be moved many kilometres along low angle thrust faults. Sometimes the rocks at the front of thrusts can be overturned into huge folds, where the rock sequence at the base of the folds is completely upside down.

The Glarus Thrust in the Alps of Switzerland. The dark rock near the top of the mountain has been thrust northwards more than 100 km over the lower rocks, as the Alpine mountain chain was uplifted by collision between the African and European plates

The Dent de Morcles fold, in the Swiss Alps near Valais. The darker rocks at the top of the mountain are the same age as those under the fold, where the lower rock sequence has been overturned by the collision of the African and European plates

Now we know how plate margins operate we can explain the parts of the rock cycle that were difficult to understand before the theory of plate tectonics was available, as shown in Table 4.21.

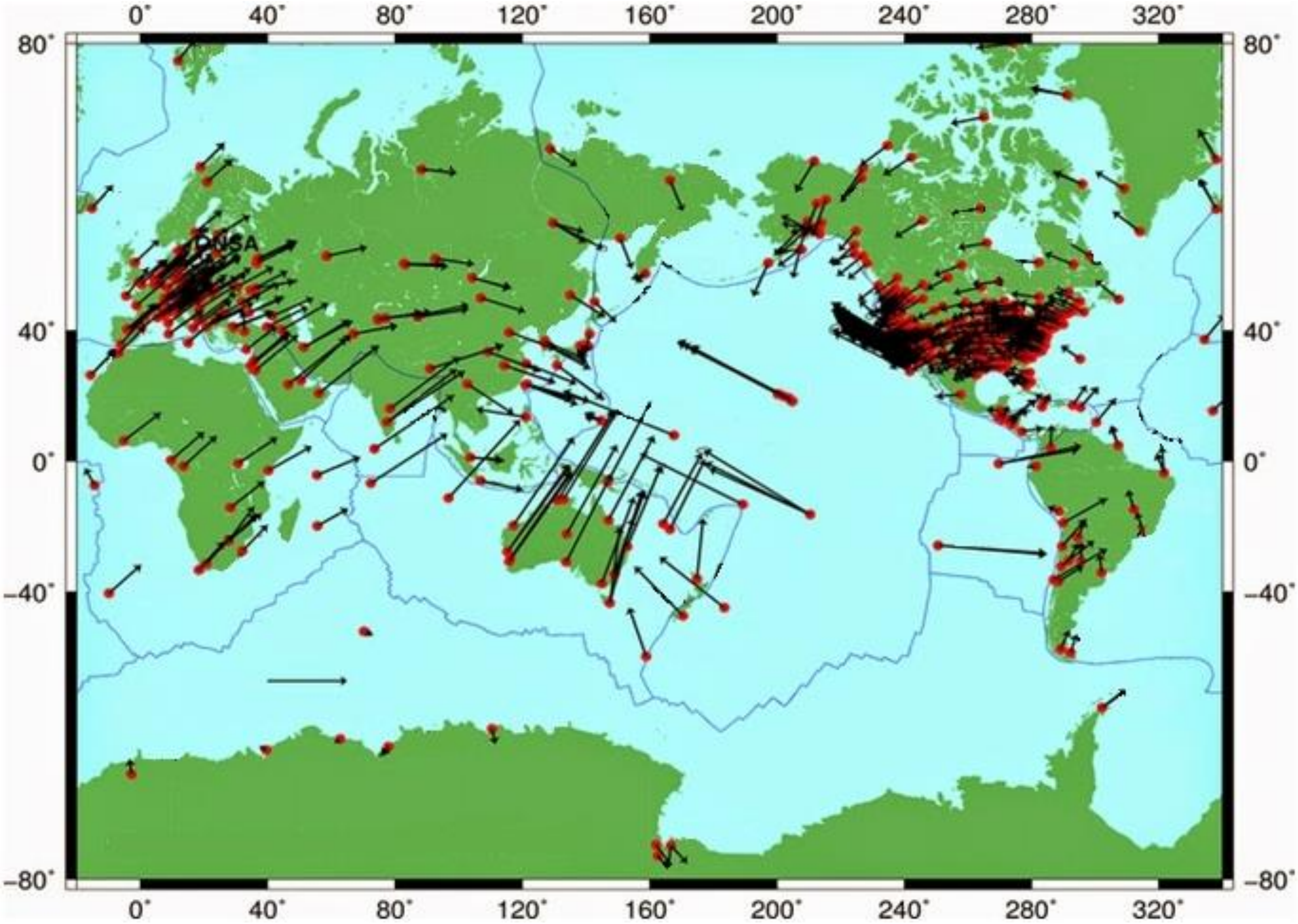
Table 4.21. Processes of the internal rock cycle now explained by plate tectonic theory

Internal rock cycle process	Plate tectonic explanation
Metamorphism	Regional metamorphism: when mountain chains are formed at ocean-continent and continent-continent plate margins, rocks are carried down to depths where the temperatures and the pressures of the overlying rocks are very high; the extra compressive stress of the colliding plates causes the rock to recrystallise
	Thermal metamorphism: intruded magmas, formed as described below, bake the surrounding rocks in a metamorphic aureole
Melting (partial melting)	At subduction zones: the subducting plate carries water with it; the water and increased temperatures cause the rocks above the plate to partially melt and the lower density magma formed by this process then rises
	At divergent plate margins: beneath oceanic ridges the mantle becomes hot enough to partially melt, generating the iron/magnesium-rich magmas that form new oceanic plate material
Igneous intrusion	As magma at plate margins rises into the cooler crust above, it cools and crystallises in large magma chambers as plutons or batholiths
Volcanic activity	If magma at plate margins and hot spots reaches the surface, it erupts; the eruptions range from relatively safe to catastrophically dangerous
Uplift	When mountain chains are formed at oceanic-continent or continent-continent plate margins, some rock is uplifted whilst other areas are forced down into the roots of the mountains. Since the mountain chain 'floats' in the solid mantle, as the overlying rock is removed by erosion the rocks beneath rise and become uplifted
Deformation	At divergent margins: as the plates are moved apart, the brittle rocks fracture into normal faults, with one side sliding down past the other
	At conservative margins: in transform fault-formation one plate slides past another and the brittle rocks fracture into strike-slip faults
	At oceanic-continent or continent-continent convergent plate margins, the enormous compressive forces cause the rocks near the surface to fracture into reverse and thrust faults; at greater depths, rocks deform through folding

4.1.4.4 Mechanism and rates of movement

Today, the movement of plates can be tracked by satellites using the Global Positioning System (GPS). This shows rates of plate movement of between about 1 and 10cm per year, about the same rate as your fingernails grow (Figure 4.33).

Figure 4.33. Rates of plate movement; the lengths of arrows show the GPS-measured speed of the plate



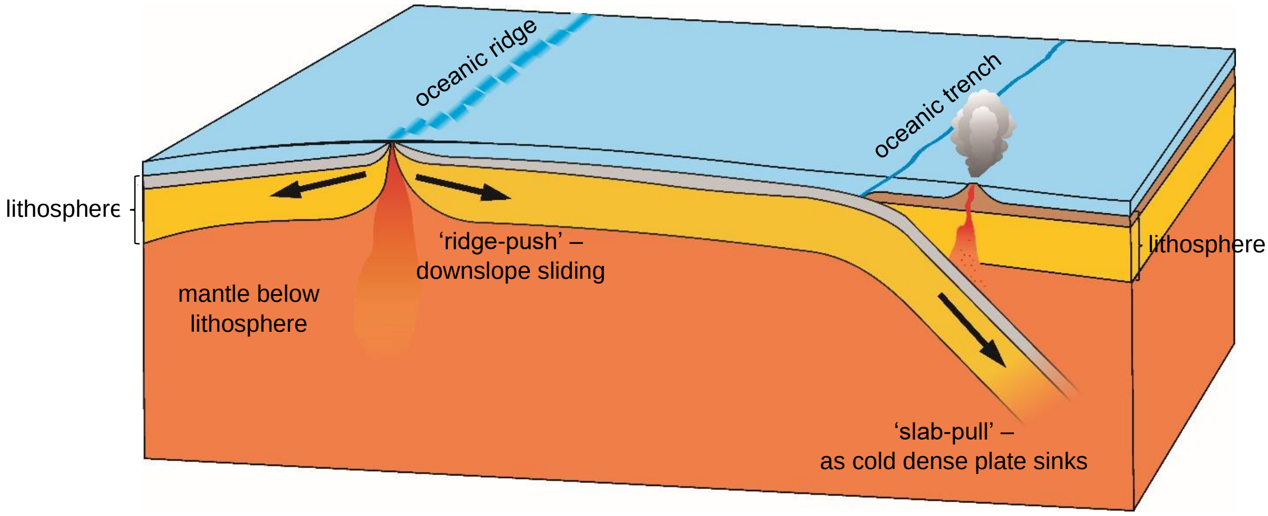
For many years it was thought that currents in the solid mantle beneath carried the plates along; heat-driven currents like these are called **convection currents**. Nowadays we can use seismic information to scan the Earth, like medical scanners can be used to scan your body. This scanning has so far questioned the idea of large-scale convection currents in the mantle. So the **mantle convection mechanism** may not be the main driving force of the movement of large plates.

Plates subduct at subduction zones because they are denser than the surrounding rocks. It seems that most plate movement can be explained by the sinking slab of cold dense lithosphere dragging the plate it is attached to across the surface; this is the **slab-pull mechanism**. This acts like a cloth with one edge hanging over a smooth table – when the edge falls to the floor, it pulls the rest of the cloth over the surface.

Where there is no great effect from slab-pull, there seems to be a push from oceanic ridges. Since oceanic ridges are higher than the surrounding sea floor, the newly formed lithosphere slides off the ridges pushing the plate ahead; this is the **ridge-push mechanism**.

Slab-pull and ridge-push now seem to be the main driving forces of large plates, although this is still being investigated; meanwhile other forces may also have effects (Figure 4.34).

Figure 4.34. Plate movement mechanisms



4.1.4.5 Evidence

We now have so much evidence to support the theory of plate tectonics that it can almost be considered as 'fact' rather than theory. This is particularly so because, like all good theories, it has pulled together a lot of ideas and offered predictions, which have been tested and found to be correct. However, like most theories, plate tectonics certainly does not explain all outer Earth processes, and some of its predictions are still being investigated.

The main lines of evidence supporting the theory of plate tectonics today are summarised in Table 4.22.

Table 4.22. The main evidence supporting plate tectonic theory

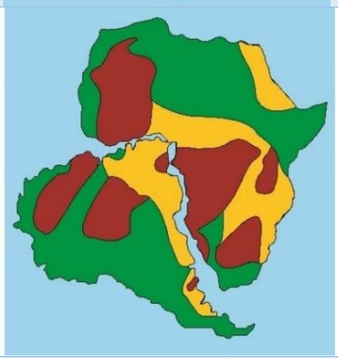
Evidence	Proposed by	Explanation	Image
Jigsaw puzzle shape	Du Toit, Wegener	The continents were once together but have split apart, which is why the shapes of their coastlines match. Later reconstructions based on the edges of the continental shelves and using computer modelling showed a very close match	
Geological evidence 'on the jigsaw puzzle'	Du Toit, Wegener	The patterns of the rocks on the continents match up, when the continents are put back together. Here, the brown-coloured rocks are more than 2000 million years old and the pale green ones are 2000 – 600Ma old	

Table 4.22. The main evidence supporting plate tectonic theory, continued

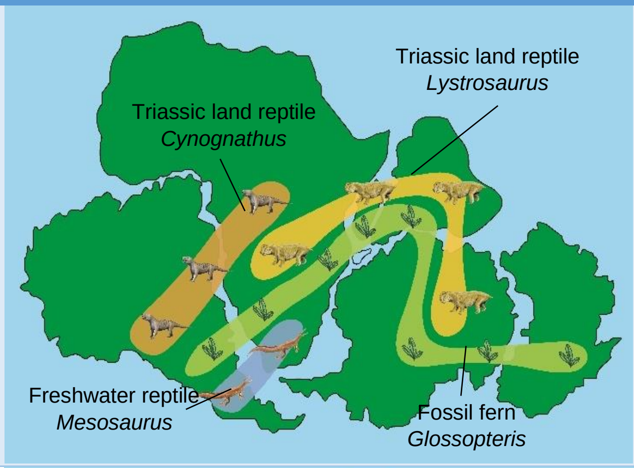
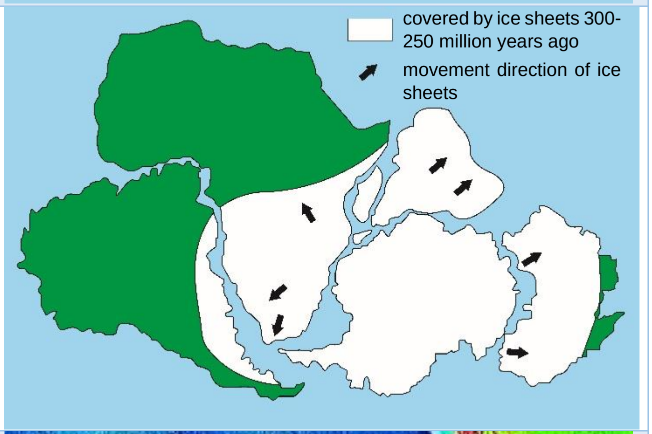
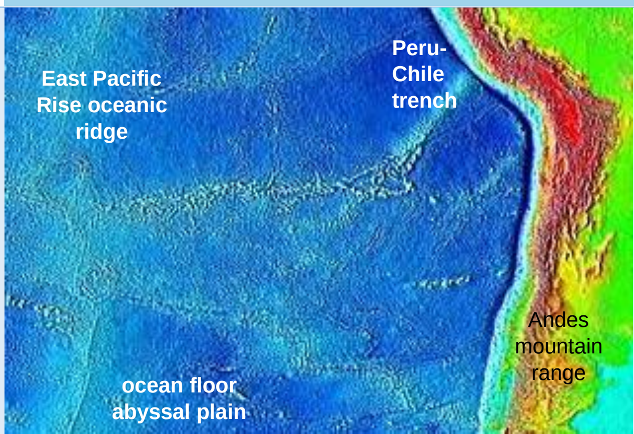
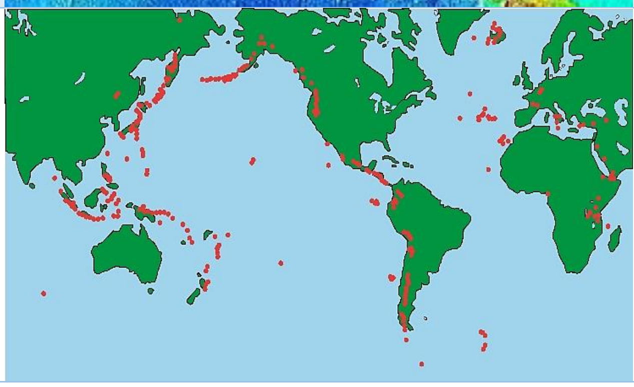
Evidence	Proposed by	Explanation	Image
Fossil evidence 'on the jigsaw puzzle'	Wegener	The places where land fossils are found fit when the continents are put together; this map shows where these fossils are found: *Cynognathus* (brown), *Lystrosaurus* (orange), *Glossopteris* (green) and *Mesosaurus* (blue)	
Palaeoclimatic evidence	Wegener	The areas of the continents that were originally ice-covered match when the continents are re-assembled; the maps show the previously glaciated area shaded	
Earth relief	Hess	Hess realised that features of the ocean floor, like trenches and oceanic ridges, could be linked together in his Sea Floor Spreading hypothesis; this was later extended, by plate tectonics, to include continental features too	
Volcano map distribution		The pattern of volcanoes on Earth, shown as red dots; they are all related to plate boundaries or 'hot spots'	

Table 4.22. The main evidence supporting plate tectonic theory, continued

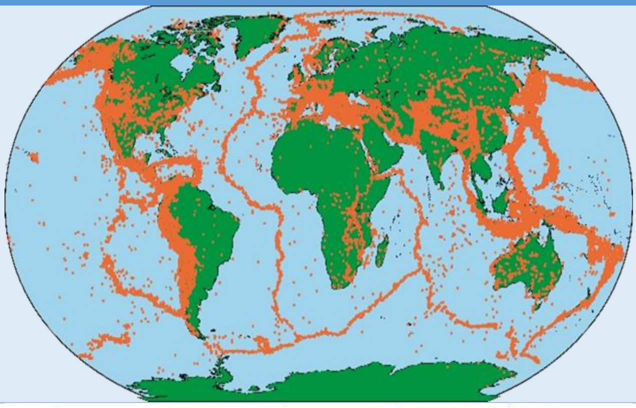
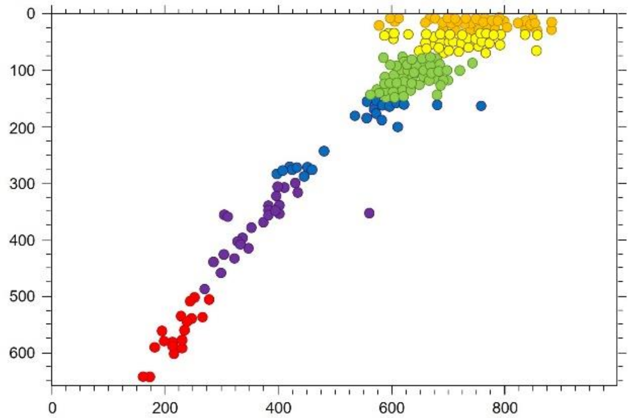
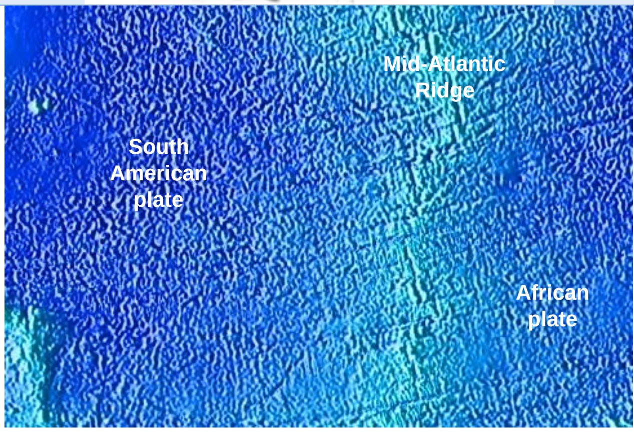
Evidence	Proposed by	Explanation	Image
Earthquake map distribution		The distributions of major earthquakes, shown here as small orange dots, show that, although there are earthquakes in many places, most occur at plate margins, particularly subduction zones	
Earthquake depths	Benioff, Wadati	The increasing depth of earthquakes along subduction zones shows the slope of the subducting plate, as explained above	
Magnetic stripes	Vine and Matthews, Morley	The symmetrical pattern of 'magnetic stripes' in ocean floor basalts on either side of oceanic ridges shows how the new oceanic lithosphere is spreading apart on either side, as explained above	
Transform faults	J. Tuzo Wilson	Where oceanic ridges are offset, there are unusual faults that move sideways between the ridges but in the same direction away from ridges; these transform faults also connect different sorts of plate margins, like the San Andreas Fault example	

Table 4.22. The main evidence supporting plate tectonic theory, continued

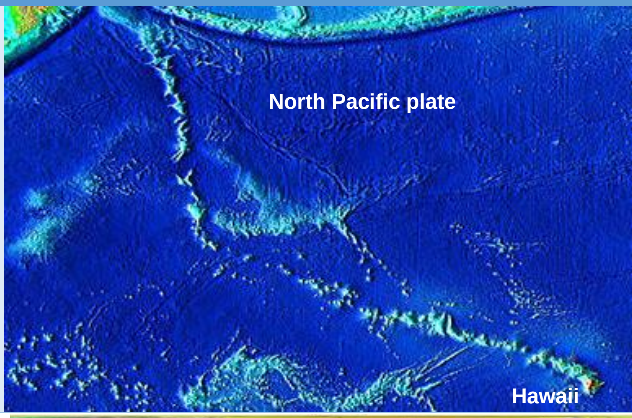
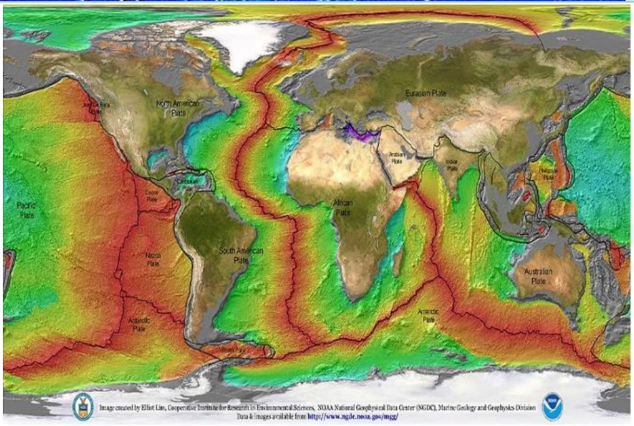
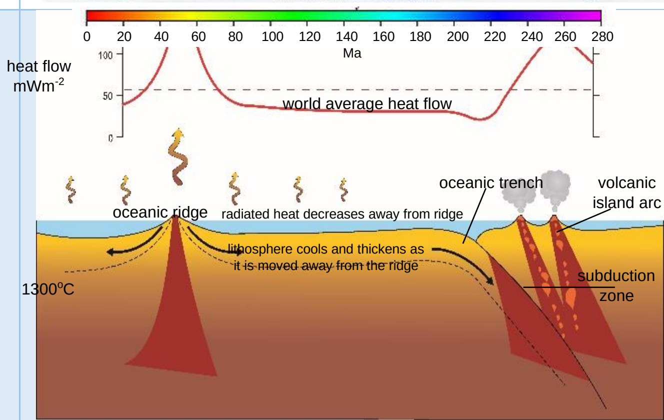
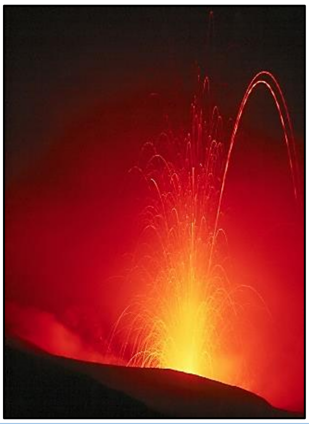
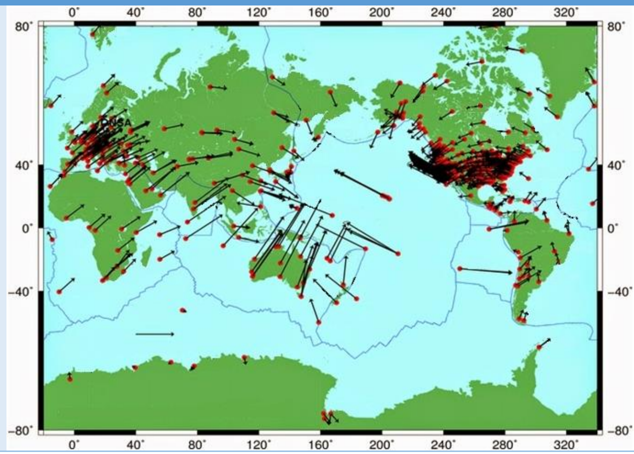
Evidence	Proposed by	Explanation	Image
'Hotspots'	J. Tuzo Wilson	As plates move across 'hotspots' in the mantle, volcanic activity erupts through them; the extinct volcanoes become older away from the hotspot, so showing the direction of plate movement, as explained above	
Age of the ocean floor		Deep ocean drilling has recovered rocks that can be radiometrically dated. This map shows the ages of the oldest rocks found in different parts of the oceans; ocean floor rocks are youngest near oceanic ridges and become older outwards	
Heat flow		Measurements of the heat flowing from the Earth show high spots at oceanic ridges and continental volcanic areas, low points at the trenches, and the slow, steady cooling of the plate as it is moved away from the ridges	
Magma composition		Eruptions at oceanic ridges and hotspots are of basalt; subduction zone eruptions are mostly of andesite and volcanic ash. The different types of magma can be explained by the different plate processes happening there	 

Table 4.22. The main evidence supporting plate tectonic theory, continued

Evidence	Proposed by	Explanation	Image
Measurements of plate movement		Modern-day plate movements are shown by GPS measurements; the longer the arrow in this diagram, the faster the movement	

Box 4.11E. Vine, Matthews and sea floor spreading

Fred Vine was Drummond Matthews' first research assistant. When Vine joined Cambridge University in 1962 he was given the job of studying the published ocean floor magnetic surveys of Matthews and others. Vine used the first computers to help calculate magnetic anomalies across the ocean ridges in the Indian Ocean, where Matthews had collected data.

Fred Vine and Drummond Matthews

In 1963 they used these data as the first geophysical test of the theory of Sea Floor Spreading, previously proposed by American Harry Hess. They published a paper called, *Magnetic Anomalies over Ocean Ridges*, a key development in the theory of Plate Tectonics. It became known as the Vine-Matthews-Morley hypothesis, recognising the work of Canadian geologist Lawrence Morley who had independently come up with the same idea a little earlier.

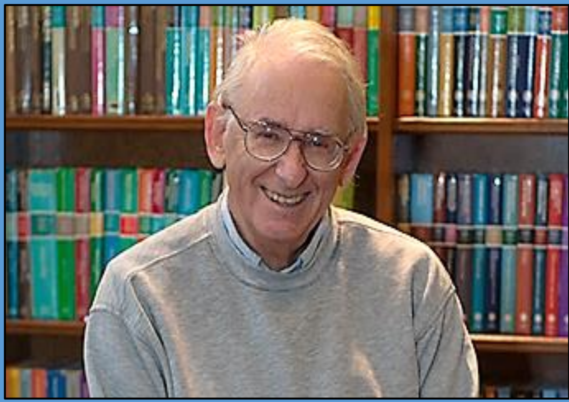
Vine and Matthews pictured Hess's seafloor spreading theory as a conveyor belt from the ocean ridges, like a tape recorder recording the Earth's magnetic reversals. The Vine-Matthews Hypothesis wasn't well-received at first, Vine said that 'it went down like a lead balloon' and it needed more evidence. This came in later work with J. Tuzo Wilson and when Vine was able to add timescales to the ocean floor pattern of palaeomagnetic reversals. The theory of seafloor spreading had been tested and proved and so became a major part of the evidence for plate tectonics.

Matthews and Vine with Dan Mckenzie

It is notable that Fred Vine first became interested in geology whilst at school studying for his geography O (ordinary) level at the age of 15. Mighty oaks from tiny acorns grow!

Pete Loader

Box 4.12E. Dan McKenzie and the plate tectonic mechanism



Dan McKenzie

When evidence for Continental Drift was building up rapidly in the early 1960s, nobody was able to suggest a mechanism for plate movement. In 1966, 51 years after Wegener clarified the problem, Dan McKenzie, who had just submitted his PhD on convection in the Earth's mantle to Cambridge University, attended a conference in New York, where he heard Fred Vine speak about sea floor spreading and magnetic anomalies. On the basis of the research carried out by Matthews and Vine and his own work in the Pacific, McKenzie introduced the overall theory of plate tectonics.

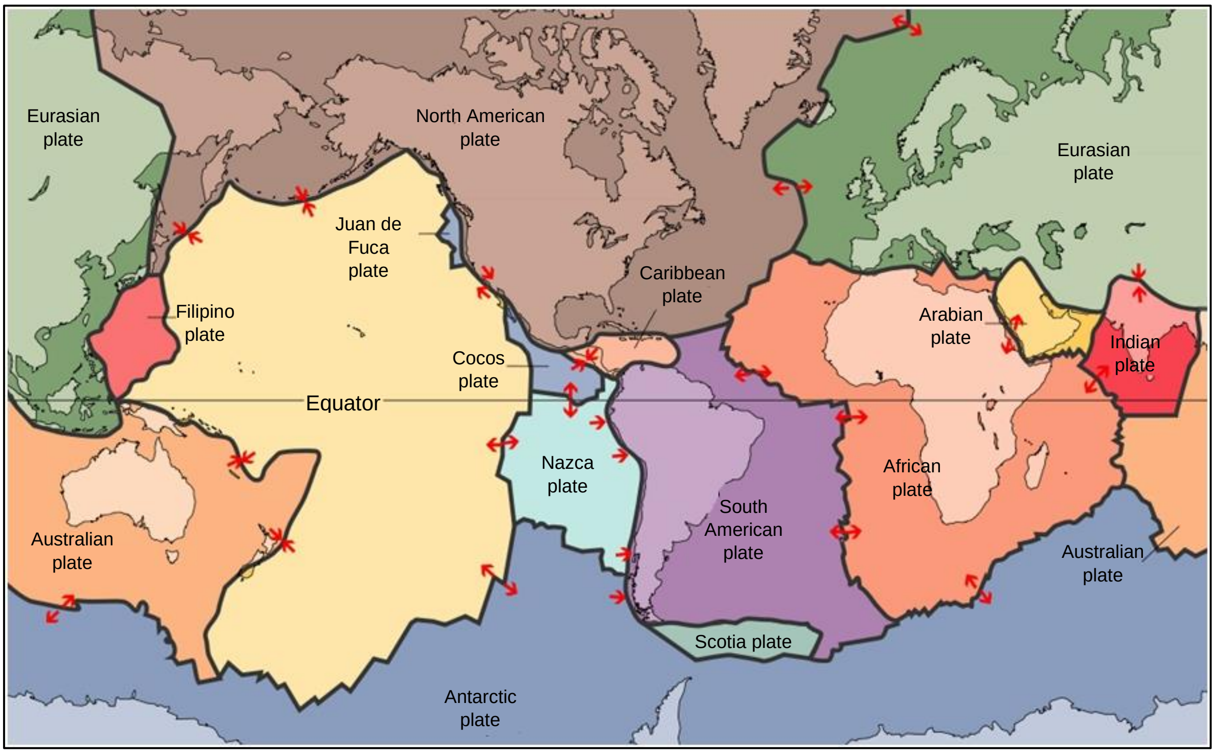
In particular he applied his knowledge of thermodynamics to the problem of how plates move, and came up with a model showing that the Earth was far more dynamic than anyone had thought. He suggested there are two layers in the mantle, each of which are in motion, controlling the movement and behaviour of the tectonic plates above. His work called "*Some remarks on heat flow and gravity anomalies"* was published in 1967.

McKenzie also modelled the generation of magmas at both mid-ocean ridges and mantle plumes/hot spots. He helped develop our understanding of how partial melting of the mantle works, and how the original composition of the magma may change with time as it moves upwards, cools and mixes with other magmas at shallower levels. McKenzie has now extended his studies to the plate tectonics of other planets, notably Venus and Mars.

Pete Loader

The many scientific investigations into plate tectonics have given the data needed to draw a detailed map of the major plates and plate margins on Earth, as in Figure 4.35. A world map can only show the major plates; there are many minor plates too.

Figure 4.35. The Earth's major tectonic plates; the red arrows show the directions of plate movement at the plate margins



4.2 Hydrosphere

Hydrosphere is the name given to all the water on our planet – from the wide oceans to the condensation you can see on the outside of a cold can of drink, and from high in the atmosphere to the bottom of the deepest borehole.

4.2.1 Continental water

4.2.1.1 Continental water sources

The main reservoir of water on Earth is the oceans, but water is brought onto the continents through the water cycle processes described in Chapter 1. Although only about 2.5% of the Earth's water is found on the continents (the rest is in the oceans), the fresh water on the continents not only has a wide range of geological effects but is also vital to life on Earth. The different sources of continental water are shown in Table 4.23.

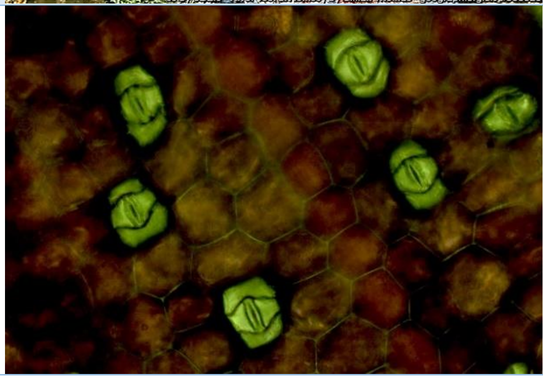
Table 4.23. Continental water on Earth

Water source	Percentage of continental water	Image	Source
Ice caps, glaciers and permanent snow	68.7		The ice cap covering Saunders Island in Baffin Bay, near Greenland
Groundwater	30.1		Groundwater emerging from the ground – Chalybeate spring, Balcombe village, West Sussex
Ground ice and permafrost (frozen soil and groundwater)	0.86		'Patterned ground' produced by permafrost in the frozen tundra of the Western Arctic National Parklands, Alaska, USA

Table 4.23. Continental water on Earth, continued

Water source	Percentage of continental water	Image	Source
Lakes	0.26		The Lake, Syston Park estate in Lincolnshire
Soil moisture	0.05		Damp soil
Atmosphere	0.04		Clouds above Knowle Lane, Sheffield, South Yorkshire
Swamp water	0.03		Freshwater swamp, Cranberry Rough near Breckles in Norfolk

Table 4.23. Continental water on Earth, continued

Water source	Percentage of continental water	Image	Source
Rivers	0.006		The River Test in Romsey, Hampshire
Biological water	0.003		A *Tradescantia zebrina* leaf viewed under microscope showing the green stomata, which release water to the atmosphere in transpiration

More than two-thirds of continental water is found in ice caps in the polar regions and in ice and snow-covered mountain areas. This water accumulates as snow that builds up into ice caps and glaciers; it is recycled as they melt.

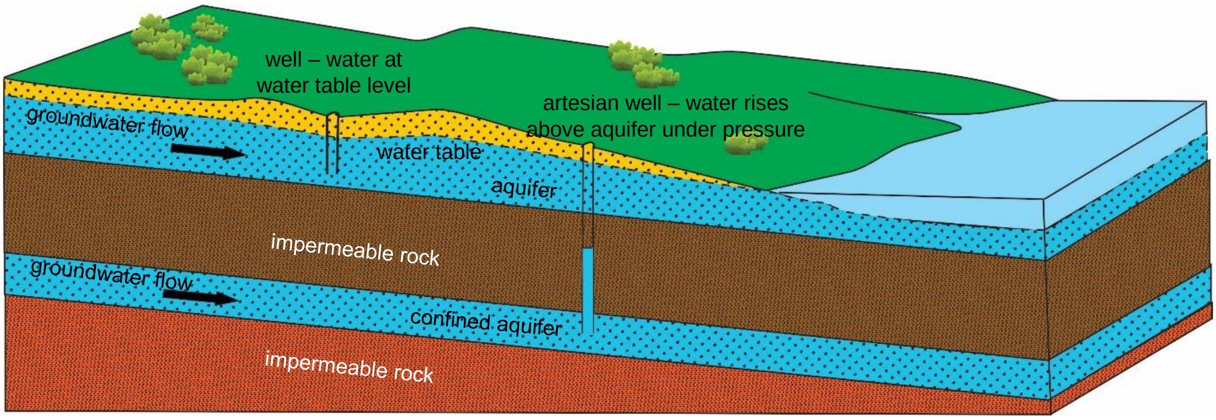
Most of the remaining continental water is found underground in rock pore spaces as groundwater or, where the ground is frozen, as permafrost. Less than 1% of Earth's water forms all the lakes, reservoirs and river systems. A tiny percentage of Earth's water is found in the atmosphere as invisible water vapour and as the visible water droplets of clouds. The atmospheric water is quickly recycled, bringing water onto the continents through rain and other types of precipitation such as snow and hail.

When it rains, some of the rain flows over the ground into gutters and small streams and then on into larger streams and rivers. However, some percolates into the soil, a process known as **infiltration**. The animals and plants in the soil use much of this soil water and some of it is recycled back into the atmosphere by plants. Plants take in water through their roots, move it up their stems and trunks, and lose it through their leaves as water vapour to the air; this is the **transpiration** process.

Some water trickles further down, into the bedrock. Water flows down through the rock until it reaches a level where all the tiny pore spaces are full of water. This is called the **saturated zone** because it is saturated with as much water as it can hold. The top of the saturated zone is the **water table**. If you look down a well, you might be able to see the surface of the water far below – this is the water table. The water in the saturated zone is called **groundwater** and it flows downhill underground until it comes out of the rock again at a **spring**, marsh, or bog, or flows into a river, lake or the sea. Groundwater flows underground only slowly, and sometimes can remain in the rock for thousands of years.

Rocks that hold water which can be extracted for use are called **aquifers**. Most aquifers are open to the air above, but sometimes the rock containing groundwater dips below an impermeable layer, so then the aquifer becomes a confined aquifer and the water it contains is **artesian water**. When boreholes are drilled into confined aquifers, the water rises to the level it had when it was first confined (Figure 4.36). If the area where it was first confined is above the Earth's surface where the borehole is drilled, the water flows out of the ground in a **flowing well**.

Figure 4.36. Aquifers



Box 4.13E. The Permo-Triassic aquifer in north west England

Cross-bedded desert dune sands of the Triassic Sandstone, Hilbre, Wirral

Specimen of the Permo-Triassic sandstone

The Permo-Triassic sandstone is the UK's second most important aquifer and occurs in a series of deep sedimentary basins. The Cheshire and South Lancashire basin formed as the crust was stretched during Permian and Triassic times, allowing blocks of rock to slide down along normal faults forming rift valleys. Thick sequences of Permo-Triassic sediments filled these valleys to a depth of more than 4 km near the centre of the basin.

The major aquifer of the Permo-Triassic Sandstone is the Triassic Sherwood Sandstone. This 600m thick sequence, contains sandstones, conglomerates, and mudstones laid down by rivers, and in lakes and dunes in a desert environment. The sandstones are usually well sorted and fine- to medium-grained with a high porosity of about 30%. Fractures increase the rock permeability, so that the sandstones are very permeable and can release most of the water that they store, with large flows coming from some boreholes. These provide groundwater sources for many industrial users as well as public water supply, agriculture, and leisure activities like golf courses. The aquifer also maintains the flow of rivers and ensures that wetlands such as the world famous wildlife reserve Martin Mere, remain flooded.

Box 4.13E. The Permo-Triassic aquifer in north west England, continued

Scanning electron microscope (SEM) image of a Permo-Triassic sandstone showing the pore spaces between the grains; width of view 4.36 mm

Birds on the shore of Martin Mere wildlife reserve, Lancashire

Maggie Williams

Box 4.14E. The London aquifer – originally artesian flow

The Chalk aquifer beneath London is a confined aquifer being beneath the impermeable London Clay. So, when boreholes were first drilled into it, they were flowing wells. These were connected to the fountains in Trafalgar Square in 1845, which originally sprayed artesian water. However, as more and more water was pumped from the aquifer, the water table fell until it was no longer artesian and electric pumps had to be installed for the fountains.

As water continued to be pumped from the aquifer, increasingly for industry, London itself began to subside as the removal of water allowed the aquifer to compress. When industry began moving out of the centre of London in the 1950s and '60s, the water table began to rise again so that surface subsidence due to aquifer pumping stopped.

However, as the water table rose back again into the London Clay, it began to cause other problems. Building foundations and tube tunnels that had been excavated into the dry London Clay became less stable as the water table rose. Carefully monitored water removal from the aquifer is now keeping the water table level steady, to reduce this problem.

Trafalgar Square fountains in London today

Chris King

4.2.1.2 Water supplies

Water may be our most important resource of all. Without water, life is impossible and humans cannot survive. Water is vital for agriculture and for many industrial needs, as well as our day-to-day household needs. Most water globally is used for agriculture; about a quarter of global water usage is by industry and only around 8% by households across the world. Nevertheless, only about 85% of the world's population has access to clean tap water. The remaining 15% of people have to collect their water from rivers, lakes or wells, even though access to clean water is known to be the most important factor in human health.

Tap water, that comes from either surface water from rivers and reservoirs or groundwater, must be treated to make it fit for use. Treatment involves settling and filtration to remove suspended muddy sediment, and chemical and biological methods to remove organic material like bacteria, algae and viruses.

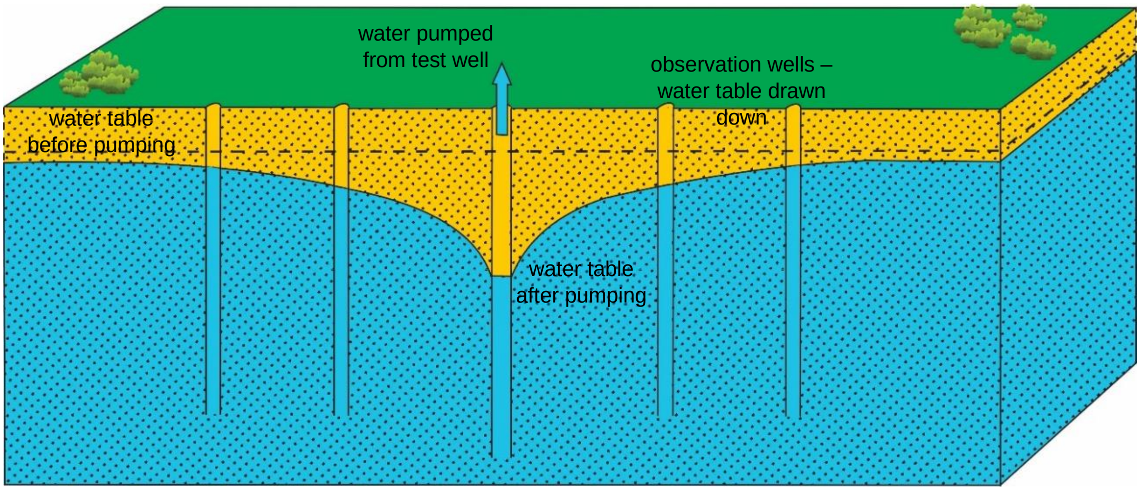
Most water across the Earth comes from surface sources, but some 40% is groundwater pumped from aquifers. Groundwater is naturally filtered through bedrock and is therefore generally much cleaner than surface water. Commercial groundwater supplies still undergo water treatment, however, even though most water taken directly from springs can be drunk safely. Indeed, much spring water is commercially bottled for sale without any treatment.

Box 4.11. Commercially sold spring water

There is a very wide range of bottled spring waters on sale.

Hydrogeologists explore for water by studying the lie of the land and the geology of an area and then drilling a test borehole, called a **well**. A series of observation wells is drilled in a line on either side of the test well and water is pumped from the test well, drawing down the water table. If the drawdown is over a wide area, then water is flowing readily into the test well and it is likely to be successful. However, if the drawdown area is small the rock is not very permeable and the well is likely to be unreliable as a water supply (Figure 4.37).

Figure 4.37. Well-testing



When a successful well has been found, the water needs to be pumped from the well (unless it is an artesian flowing well). Pumping in the past used to be by hand or huge steam engines. Nowadays, hand pumps are still used in rural areas, together with wind pumps, but elsewhere groundwater is pumped using diesel or electrical pumps.

Box 4.12. Groundwater pumping methods

Victorian pumping station that once contained a huge steam pumping engine, London

Wind pump near High Thurney Farm, Queniborough, Leicestershire

Diesel groundwater pump in use today, Staffordshire

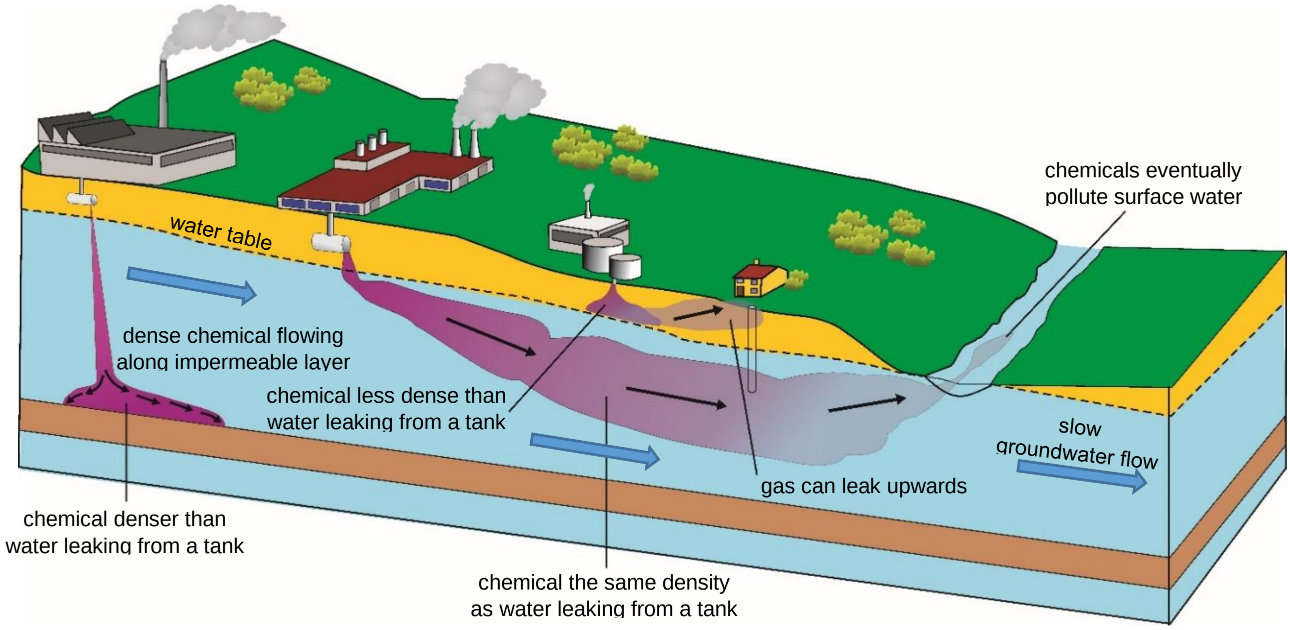
4.2.1.3 Water contamination

Surface and groundwater can become contaminated by natural sources, but most water contamination is by human activity. Contamination can be by light (low density) fluids like fuels which float on surface water or on the water table; by heavy fluids (high density) that sink to the bottom of reservoirs or aquifers; or by a wide range of materials suspended or dissolved in the water.

The main contaminants of surface water are from urban activity. They include salt and oil from roads, industrial contamination from leaking chemical and fuel tanks and mine spoil heaps and individuals disposing of cleaners, detergents, oil, paints and garden products by pouring them down the drain. Agriculture also produces waste, including animal wastes, fertilisers and pesticides.

There is underground pollution of groundwater too. This may come from urban landfill sites, from leaking sewers and septic tanks, from industrial pipelines and from poorly constructed wells in urban and rural areas (Figure 4.38).

Figure 4.38. Plumes of groundwater pollution



Environmental geologists work to prevent the pollution of both surface and groundwater supplies. They seek areas of impermeable rock for waste disposal, so that fluids from the wastes do not leak into and pollute water supplies; they also monitor industrial and landfill waste disposal sites for leakage. Protecting the environment may include collecting regular surface water samples and testing these for contamination, and also monitoring test wells around potential contamination sites. When groundwater contamination does occur, it can be cleaned up, but remediation methods are very expensive.

Box 4.15E. Polluted mine water from a flooded deep coalmine

This mine tunnel in the cliffs in Spittal, was a drainage outlet for the Scremerston coalmine which closed in 1944. When pumping stops, mines eventually flood. Water contaminated by orange iron oxides, formed by oxidation of the pyrite in the coal, flows out. Here it flows into the sea from the old workings, staining everything in its path. Very few plants and animals can live in the polluted water. The coal seams here were only about 0.75m thick and were some of the earliest to be mined in Britain.

Iron oxide-polluted water flowing from an old mine tunnel, Spittal, Northumberland in northern England

Elizabeth Devon

4.2.2 Oceanic water

Ocean and seawater cover more than two-thirds of the Earth's surface today, although there have been times in the geological past when oceans covered much greater or much reduced areas. The Earth's major deep oceans include the Pacific, Atlantic, Indian, Arctic and Southern Oceans, and there are many seas on the continental shelves.

4.2.2.1 Water composition

Seawater contains about 3.5% of dissolved salt, so the salinity of normal seawater is 3.5%. The salt is mainly ions of sodium and chlorine, but also includes magnesium, calcium, potassium, hydrogen carbonate, sulfate and other minor ions. These have been brought into the sea by rivers in the distant geological past and have concentrated there.

Where fresh water from rivers mixes with seawater, salinity is reduced and the water becomes brackish. Elsewhere, in strongly evaporating shallow seas, removal of the water causes salinity to increase until the water eventually becomes so supersaturated in salt that crystals form and settle to the seabed. Seawater tastes nasty, but supersaturated seawater tastes really horrible and can sting your eyes.

Fresh water is less dense than salt water so that, when river waters flow into the sea, their water floats on the surface without mixing for a long time. There is usually a clear boundary between the fresh water above and the more saline seawater below.

4.2.2.2 Tides

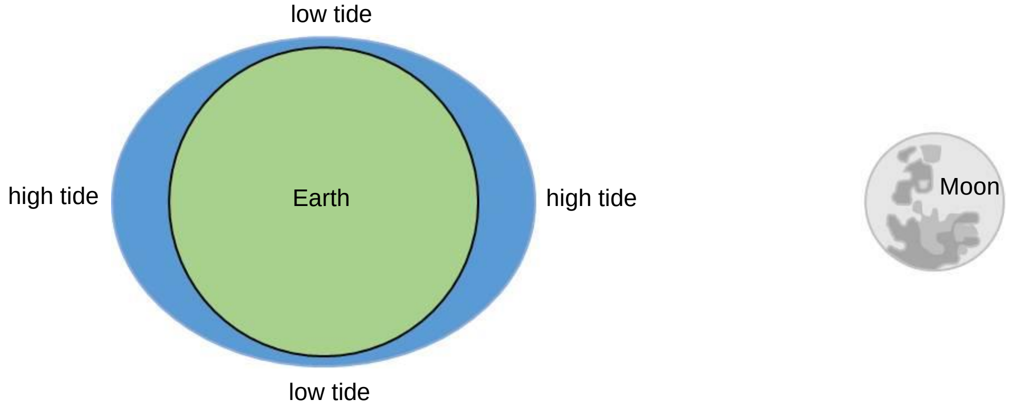
Coastal areas are affected by tides, which are caused by the gravitational pull of the Moon and the Sun linked to the rotation of the Earth.

Figure 4.39. Low tide and high tide – the Humber Bridge from north Lincolnshire to the East Riding of Yorkshire

Most coastal areas experience two high tides separated by two low tides each day. The tide rises as a flood tide over several hours until it reaches its highest level, high tide. Then the tide slowly ebbs until it reaches its lowest point, low tide, before the cycle begins again. Rising and falling tides move the wave zone up and down beaches and rocky coastal areas. Meanwhile, tidal flats become flooded by fairly still water, before it drains away, leaving them exposed again.

The main cause of tides is the gravitational pull of the Moon. The pull of the Moon causes a high tide on the side of the Earth the Moon is on, and on the opposite side too, with low tides in between, as shown in Figure 4.40. So as the Earth rotates beneath the Moon once a day, most areas experience two high and two low tides per day. Since the time for this to happen is around 25 hours, the tidal pattern moves on by about an hour each day.

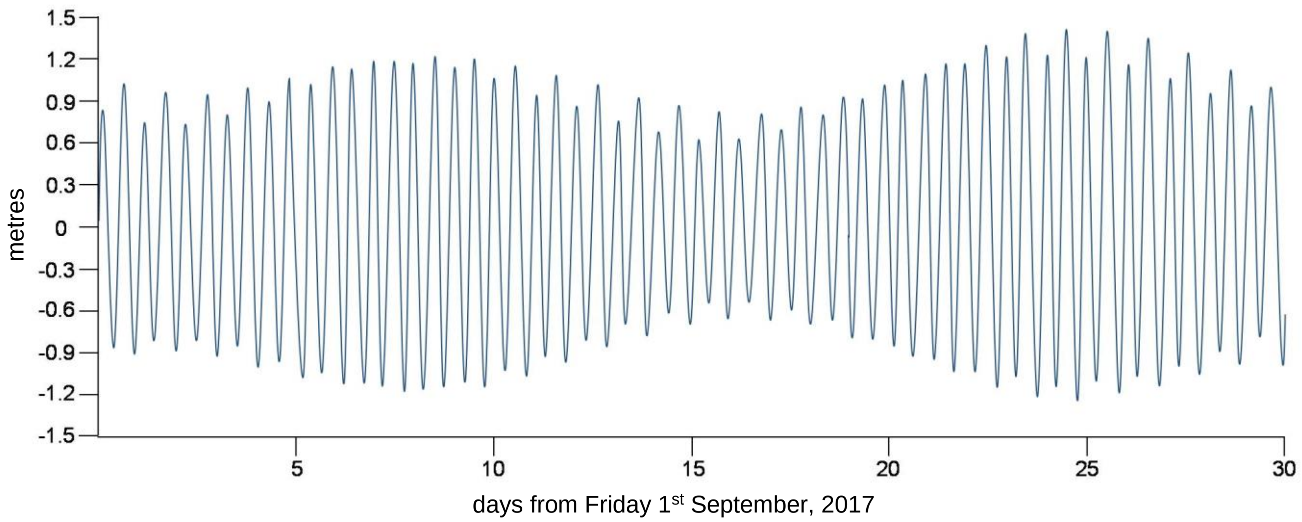
Figure 4.40. The Moon causing tidal bulges



Although the Sun is very much further away, it is much larger than the Moon and so also has an effect. This means that when the Moon and Sun are aligned, there is greater pull, with higher high tides and lower low tides – these are the **spring tides**. (Spring tides have nothing to do with the season of spring, although, confusingly, the highest spring tides are usually in the spring and autumn). However, when the pull of the Moon and Sun are at right angles to each other, their overall gravitational pull is reduced, with lower high tides and higher low tides – the **neap tides**.

The result for most coastal areas is a tidal chart like the one shown in Figure 4.41. The chart shows that each day has two low and two high tides, but that the high tide is highest, and the low tide is lowest, at around the 8th and 25th days – these are the days of spring tides. Neap tides occur around the 3rd and 16th days. If you want to see the widest expanses of beaches and tidal flat muds, visit the coast at low spring tide. However, if you want to see the greatest coastal erosion of steep coastlines, visit at the highest spring tides when the tides bring the waves highest up the beach and cliffs. At the same time, tidal flats are completely flooded.

Figure 4.41. Tidal changes – an example from Bridgeport, Connecticut, USA



4.2.2.3 Waves

When you watch waves at the seashore, it seems as if they are moving huge volumes of water. However, if you watch anything floating out beyond the surf line, you will see that it just bobs up and down and is hardly moved sideways. This is because, as a wave crest passes, the water rises and moves forward a little, whilst as a wave trough passes, it falls and moves backwards a little, so that the surface water just moves around in a vertical circle. Deeper beneath each wave, the water moves in smaller circles until the wave dies away at depth. So although waves in stormy open oceans can be many metres high they cause no overall horizontal movement of water.

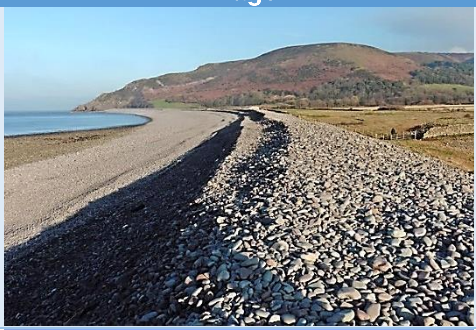
As waves reach the coast, the friction at the sea bed increases, so the bottom of the wave slows down, causing the wave to grow higher. Eventually it becomes high enough to collapse forward into a breaker. When breakers are high, they are good for surfing. When the breaker collapses onto the beach, a rush of water floods up the beach, but then flows back under gravity – until the next wave comes.

Figure 4.42. Waves – large and small

Waves are caused by winds blowing over the sea surface in the open ocean. Friction between the wind and the water causes small waves to rise, and these are pushed onward by the wind. So the longer the time and the greater the distance of ocean over which wind blows, the larger the waves become; stronger winds produce bigger waves as well. The best surfing beaches, therefore, with the largest waves, are found opposite open oceans.

Waves and tides working together produce a range of coastal features.

Table 4.24. Coastal features produced by waves and tides

Process	Description	Image	Source
Storm beach-formation	When a storm coincides with high spring tide, a storm surge pushes the storm waves even further up the beach than normal, building a bank of pebbles and shingle at the back of the beach		A storm beach at the back of Bossington beach in North Devon
Tidal flat-formation	During high tides, and particularly at high spring tides, tidal flats are covered by water; mud settles out of the still water to form a layer each time the flat is flooded; the layers build up over time into tidal flats		Tidal mud flats in the Lower Halstow Creek estuary, Kent
Spit-formation	When waves hit a beach at an angle, the rush of the collapsing wave pushes sand diagonally up the beach, but the wave flows straight back down the beach, carrying the sand. So sand is moved steadily along the beach in a movement shaped like the teeth of a saw. At the end of the beach, the sand is carried out to sea, forming a spit		Hurst spit, Hampshire

4.2.2.4 Large-scale circulations of fluids on Earth

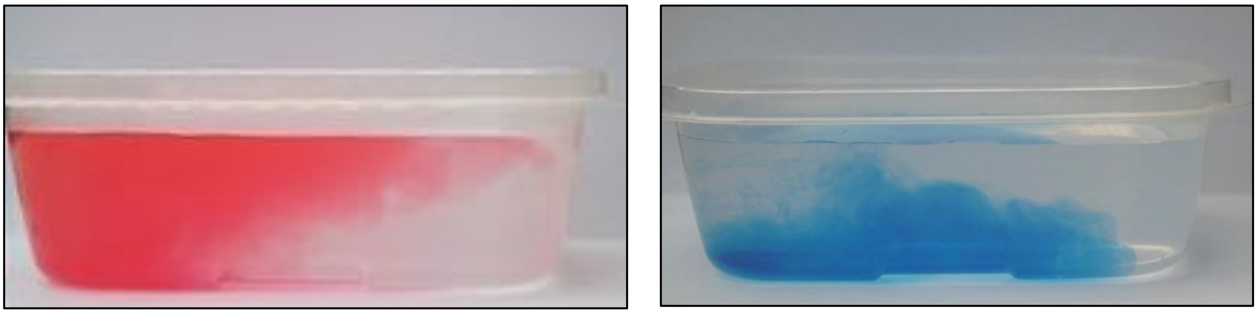
Both the oceans and the atmosphere are fluids and similar forces act on these fluids producing similar effects.

When both types of fluid (water and air) are warmed, they become less dense than the surrounding fluid and so rise; when they reach upper, cooler conditions they flow outward. In the oceans, this means that water which has been warmed in tropical regions flows as currents out across the ocean surface. As the warm water flows away, cooler water from below rises; this water is often rich in nutrients and so these are areas of prolific ocean life. Meanwhile, in the atmosphere, rising warm air exerts less pressure on the Earth's surface, causing **low pressure**. The warm air rises and flows outwards in the upper atmosphere. These fluid flows are part of convection.

When the fluids are cooled they become denser and sink. In oceans, the coldest water is in the polar regions. This cold water sinks and flows over the deep ocean floor. In the atmosphere, cold air sinks, causing **high pressure**. When it reaches the Earth's surface, it flows across the surface towards low-pressure areas; this surface flow of air is wind. These flows complete the convection cycle.

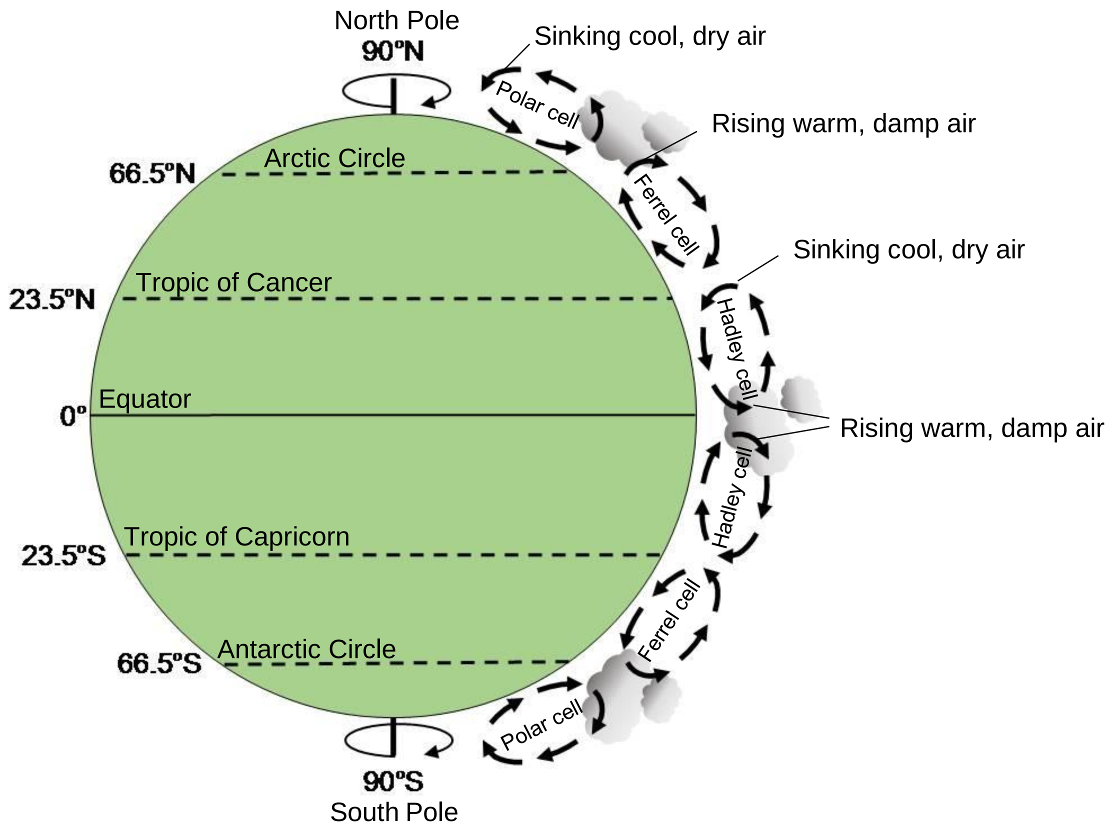
Flows of warm and cold fluids happen at much smaller scales too. You can often see the shimmering of warm air rising over a heater or a fire; the opposite happens if you open an upright freezer in bare feet, you can feel the cold air flowing downwards over your skin. If you are having a bath and add more hot water, you can often feel the hot water flowing over the surface, whereas if you add cold water, it flows across the bottom of the bath and is not so pleasant (Figure 4.43).

Figure 4.43. Warm red-coloured current flowing over the surface; cold blue-coloured current flowing over the bottom – both in a plastic lunch box



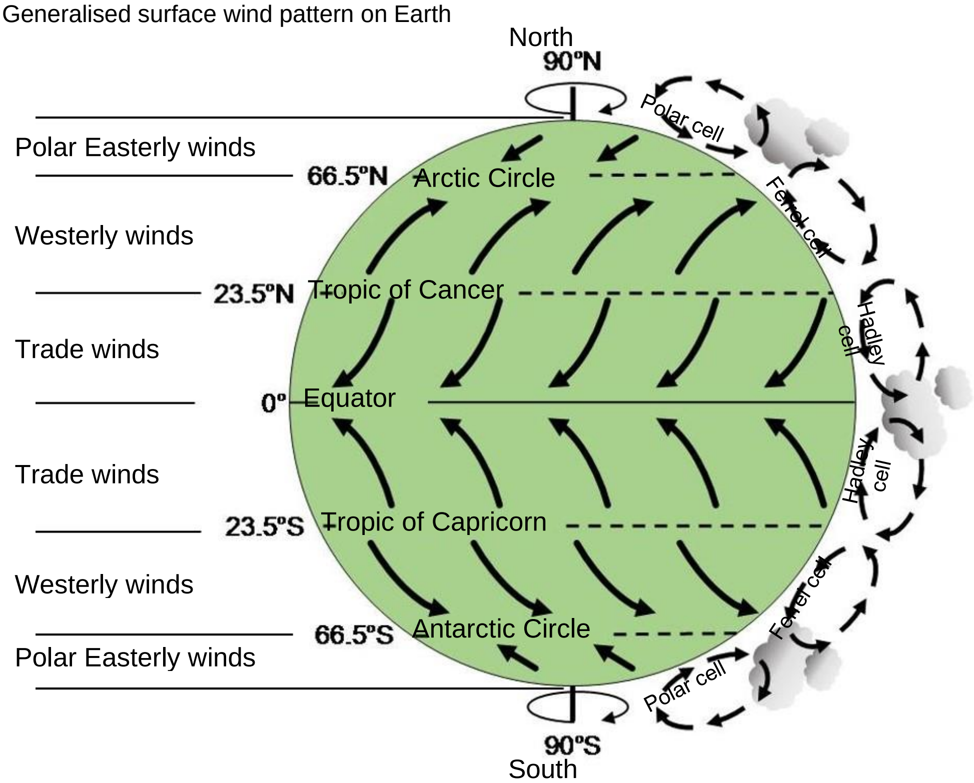
Equatorial areas, being very warm, have rising air and low pressure. The warm air flowing across the upper atmosphere becomes cooler and sinks over subtropical desert areas, as shown in Figure 4.44. When this sinking air reaches the ground, some of it flows back towards the Equator to complete the tropical/sub-tropical circulation called the Hadley cell. But some of the sinking air flows towards the poles. As it crosses the warm seas, it becomes warmer and eventually rises. In the upper atmosphere, some air flows back towards the Equator, to complete the Ferrel circulation cell. Some blows towards the poles though, becoming cooler as it does so. This eventually sinks over the poles and flows Equator-wards at the Earth's surface, completing the Polar circulation cell.

Figure 4.44. Air mass circulation on Earth



This simple atmospheric circulation pattern is affected by the rotation of the Earth. Air flows in the Northern Hemisphere are deflected clockwise, while those in the Southern Hemisphere are deflected anticlockwise. This gives a generalised surface wind circulation pattern as in Figure 4.45.

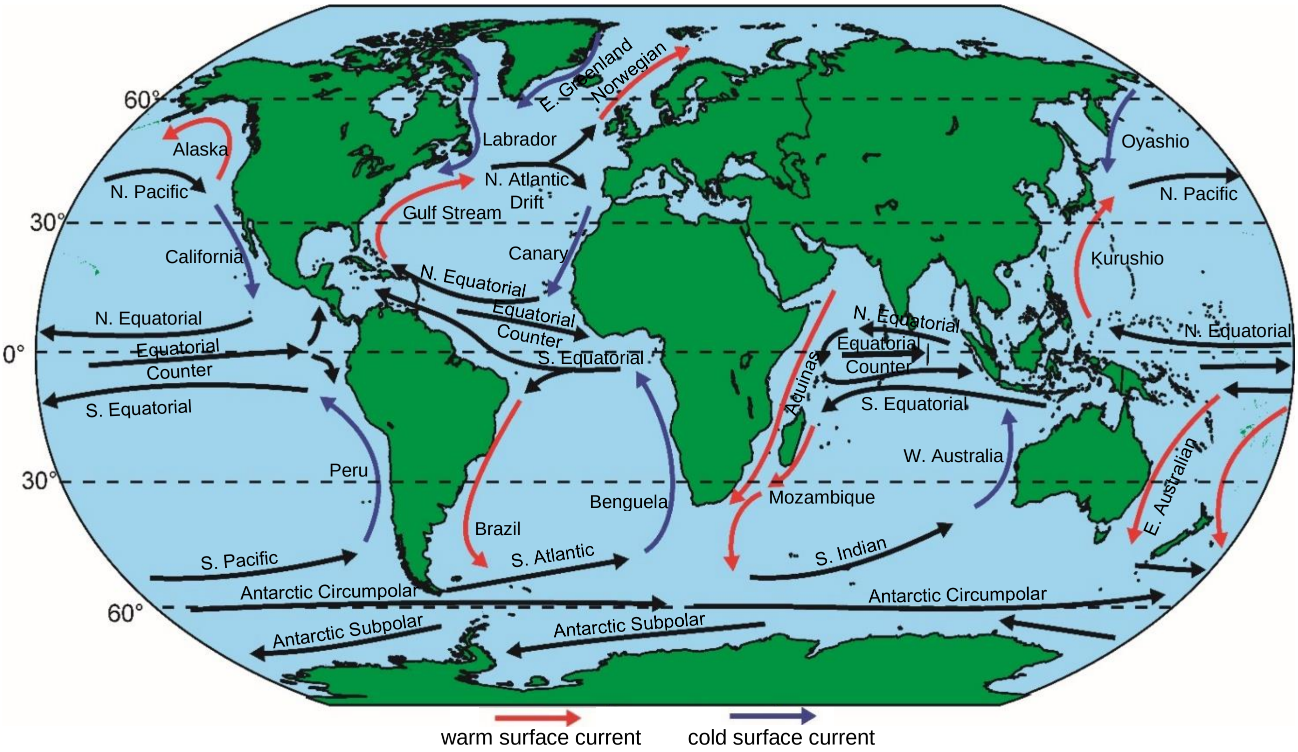
Figure 4.45. Generalised surface wind pattern on Earth



The general surface winds at the base of the Hadley cell are the easterly Trade Winds. Those at the bottom of the Ferrel cell are the Westerly Winds (winds blowing from the west) and the Polar cell surface winds are the Polar Easterlies.

The global winds drag on the ocean surface, causing it to move in the direction the wind is blowing and adding to the natural flow direction – clockwise in the Northern Hemisphere and anticlockwise in the Southern Hemisphere. So the major surface ocean currents rotate clockwise in the Northern and anticlockwise in the Southern Hemisphere, driven by the rotation of the Earth (Figure 4.46).

Figure 4.46. Surface ocean circulations



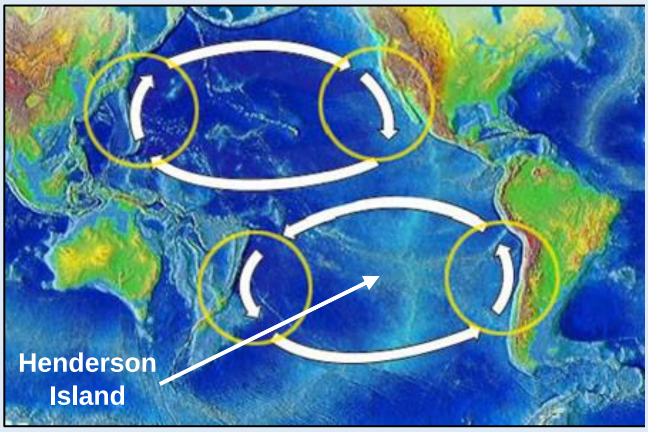
Box. 4.13. Ocean currents and the most polluted island on Earth

Henderson Island in the south Pacific Ocean is uninhabited and one of the islands furthest from any continents. Scientist Jennifer Lavers, who led an expedition to the island in 2015, was amazed by the amount of plastic pollution that had built up there. She said, “I’ve seen a lot of plastic on my travels – in some of the most remote places – but Henderson Island tops the cake. The quantity of plastic is truly alarming and takes your breath away.” The expedition found up to 671 pieces of plastic on every square metre of beach and estimated that the beaches of the whole island contained more than 37 million bits of debris – the world’s worst recorded plastic pollution. It was badly damaging the wildlife: a turtle was found strangled by plastic string and hermit crabs were making their homes in plastic cosmetic pots.

The pollution gathers near the centre of the South Pacific Gyre. This surface ocean current circulates anticlockwise in the south Pacific Ocean, carrying floating debris towards the centre.

Jennifer Lavers added, “Once plastic is in the ocean, it is virtually impossible with current technology to get it out. The focus needs to be on preventing it from getting there in the first place.” She saw lots of plastic toothbrushes washed up and said that toothbrushes made of bamboo and wood fibre cost the same as plastic ones but would not pollute the Earth for hundreds of years. Everyone should stop littering beaches and use less plastic by switching to less harmful materials.

Box. 4.13. Ocean currents and the most polluted island on Earth, continued

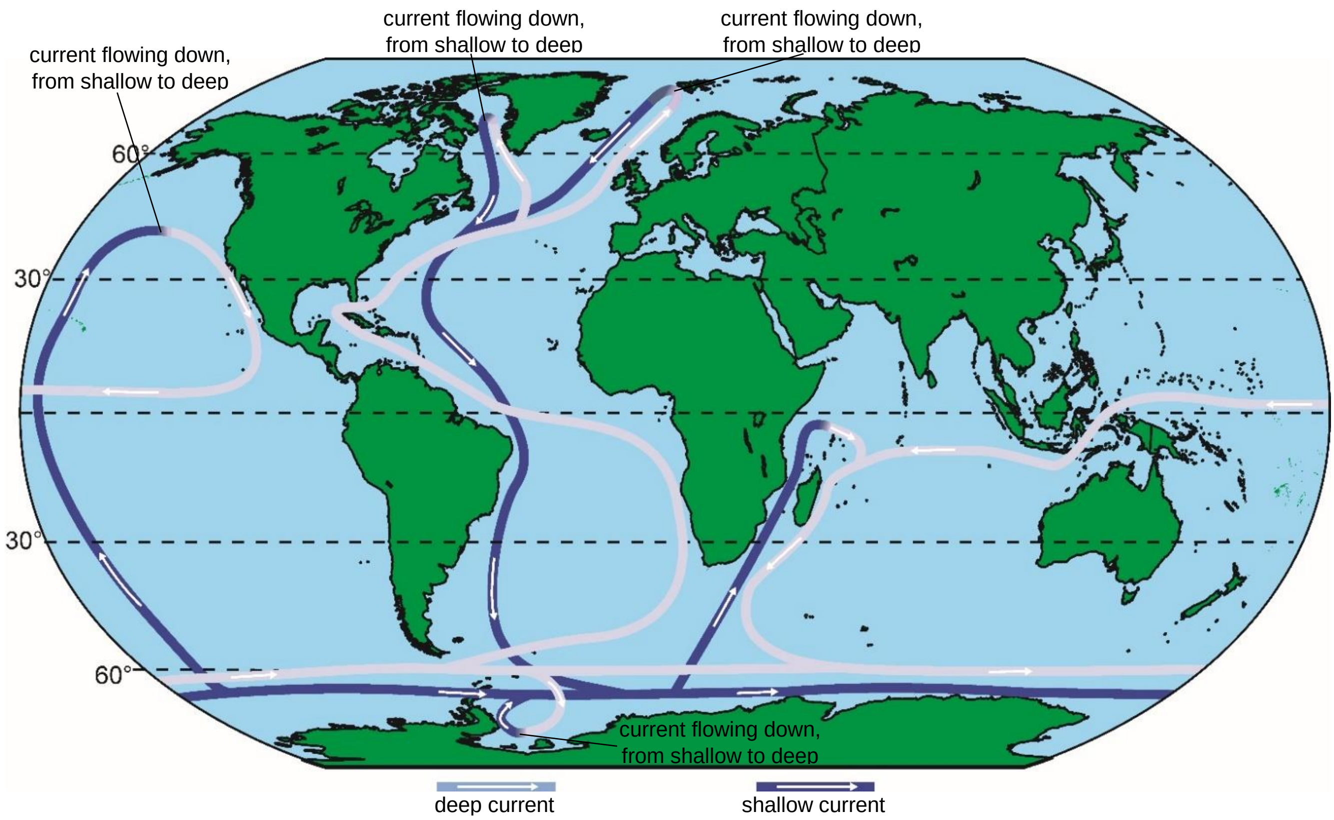


Circulating surface ocean currents in the north and south Pacific Ocean

The polluted beach of uninhabited Henderson Island in the remote south Pacific Ocean

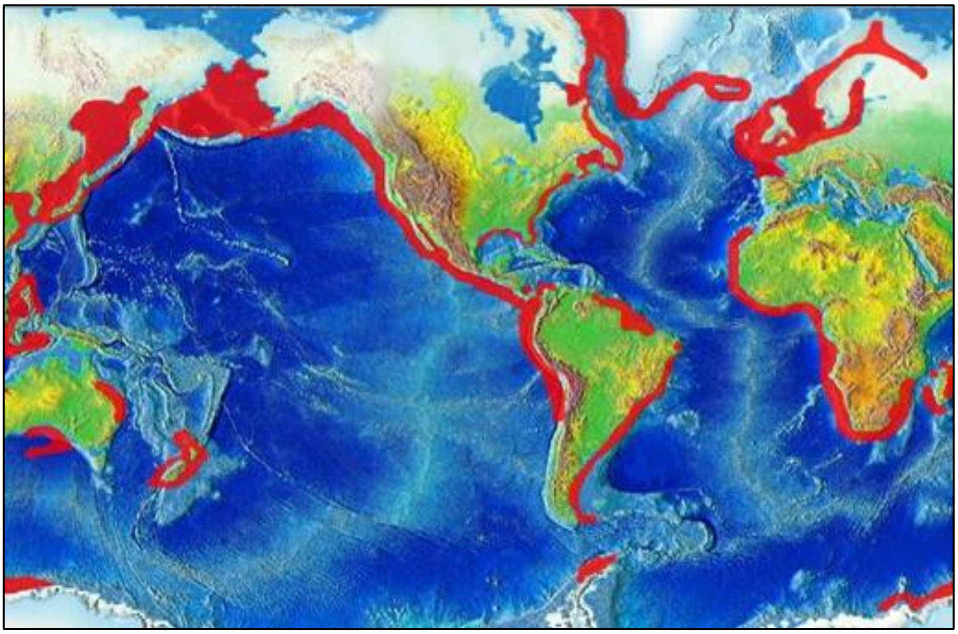
Surface ocean currents link to deep ocean currents. Where warm ocean currents flow towards the poles, they become cooler, and more saline due to evaporation. This increases their density, so they sink near the poles as cold, dense salt-water currents. This produces the shallow-to-deep circulation pattern shown in Figure 4.47.

Figure 4.47. The shallow-to-deep circulation pattern of the Earth's oceans



The upwelling of cold, nutrient-rich deep ocean water, caused by winds blowing the warmer surface waters away, results in blooms of plankton; these provide the food in the best fishing grounds on Earth, shown in Figure 4.48.

Figure 4.48. The best fishing grounds, shown in red, produced by the upwelling of cold deep ocean waters



The interactions show how closely the Earth's systems are interlinked. The flow of atmospheric air, or wind, drives the surface ocean currents, while the ocean warms the air, contributing to atmospheric circulation. Then ocean upwelling of nutrient-rich water causes abundant sea life. The atmosphere, hydrosphere and biosphere are clearly closely bound together by these processes.

4.3 Atmosphere

The Earth's atmosphere, like the other spheres, is critical to life on Earth. The atmosphere has several layers, but the most important layer for life is the lowest layer, the troposphere; this is the most oxygenated and has the right temperature for life. The troposphere is around 16 km thick at the Equator, thinning towards the poles. If the Earth's crust is equivalent in thickness to a postage stamp stuck onto a football, then the troposphere is like a half-thickness postage stamp stuck on top. The layer above the troposphere is also important because it contains ozone, which shields us from the harmful ultraviolet radiation from the Sun (Figures 4.49 and 4.50).

Figure 4.49. The 'blue marble' Earth showing the very thin layer of atmosphere in purple around the outside

Figure 4.50. Space shuttle *Endeavour* orbiting in the outer atmosphere, showing the orange troposphere layer and the white layer above that contains ozone

4.3.1 Atmospheric composition

As the early Earth cooled down more than 4000Ma ago, any early atmosphere that formed was swept away by the solar wind and the Earth was bombardment by meteorites. But, as the bombardment declined, intense volcanic activity added water, carbon dioxide and other gases like nitrogen, methane and sulfur to a new atmosphere. Much of the water fell as rain from the atmosphere, forming the first oceans.

This early atmosphere contained no oxygen. Some 2500Ma ago, the first bacteria to photosynthesise evolved in the oceans. The bacteria absorbed carbon dioxide from the atmosphere and released oxygen through photosynthesis (Figure 4.51). The first-formed oxygen reacted with other materials such as iron, and so it was not until about 200Ma later that free oxygen began to build up in the atmosphere.

Figure 4.51. Microscopic ocean bacteria, which photosynthesise, absorbing carbon dioxide, releasing oxygen

The free oxygen in the atmosphere made the Earth's surface an oxidising environment for the first time, but it wasn't until the end of Precambrian time, the start of the Cambrian 541Ma ago, that animals using oxygen became abundant on Earth. Since then the percentages of the different gases that make up the atmosphere have continued to change. The atmosphere today contains 78.09% nitrogen, 20.95% oxygen, 0.93% argon and 0.04% carbon dioxide, with small amounts of other gases. It also contains a varying amount of water vapour gas ranging up to more than 4%, but this is not included in percentage calculations of atmospheric gases because it changes so much.

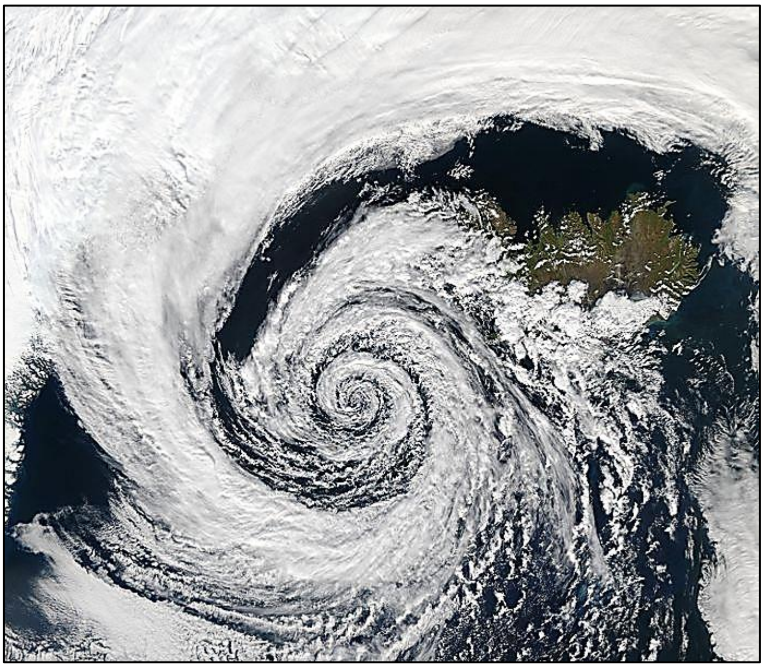
The measure of the amount of water vapour in air is its humidity. When air reaches 100% humidity, it can hold no more water vapour. Then the invisible gas begins to change state, to tiny liquid water droplets (in condensation, mist, fog, dew or cloud). The droplets may then gather together to form water droplets or ice crystals, which fall as rain or other sorts of precipitation. Very humid air feels unpleasant if it is hot (often called 'torrid') or cold (often described as 'raw'), so that people generally prefer dry air conditions.

4.3.2 Atmospheric flow

Global airflow is driven by the different amounts of heating of the air causing density differences, together with the spin of the Earth, as shown in Section 4.2.2.4 above.

These are key factors in more local airflows too. Hot air masses rise across regions of the Earth; as they do so, the rotating Earth causes them to spin, anticlockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. These rising air masses, causing low pressure on the Earth's surface, are called cyclones. At the base of cyclones, at the Earth's surface, the air flows inwards as spiralling winds that are picked out by the cloud formations of Figure 4.52.

Figure 4.52. The spiralling clouds of a cyclone near Iceland on 4 September 2003



Clouds form because rising air cools and cooler air can hold less water than warmer air. The water forms cloud droplets, which then produce rain or snow. So cyclones normally cause windy and wet conditions.

When cyclones develop over the sea in tropical areas, the warm sea contains a lot of heat which can turn cyclones into much larger hurricanes or typhoons (Figure 4.53). When hurricanes and typhoons hit land they bring hurricane-force winds and very heavy rain. The strong winds can force seawater onto the coast in storm surges that can be very damaging when they coincide with high tides.

Figure 4.53. Hurricane Isabel in the North Atlantic Ocean in 2003, with the characteristic eye in the centre. Highly damaging winds of 265 kmh^{-1} were recorded with many millimetres of rain.

Elsewhere, cold, sinking air masses also rotate, clockwise in the Northern Hemisphere and in the opposite direction in the Southern. These anticyclones are areas of high pressure (Figure 4.54). The gently sinking air of high pressure areas causes lighter winds than cyclones and little wind at all in the centres. As the air sinks it warms and can hold increasing amounts of water vapour, so anticyclones have little cloud or rain.

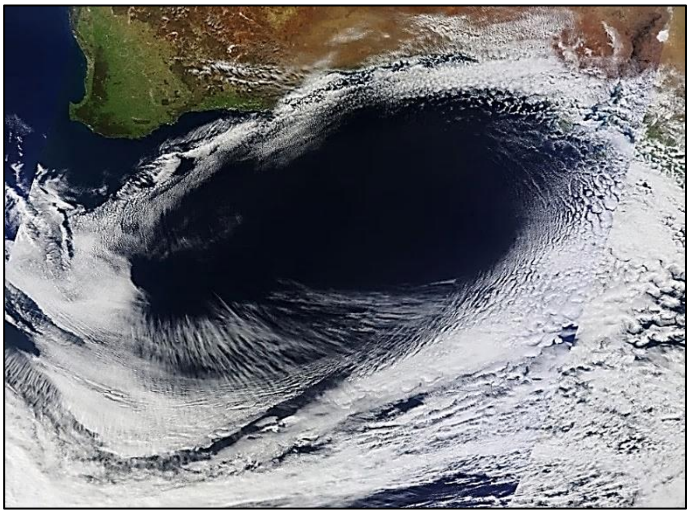


Figure 4.54. An anticyclone near southern Australia in 2012. Winds and cloud trails spiral anticlockwise (they would spiral clockwise in the Northern Hemisphere) but the sinking, warming air produces no cloud in the centre

At even smaller scales, sinking cold air can trap pollution, smoke and cloud beneath, which can be very unpleasant in some cities (Figure 4.55). In other areas, strong heating of the land can cause eddies of rising warm air called thermals, where birds and gliders can soar for many hours (Figure 4.56).

Figure 4.55. Pollution smog in London in 1952

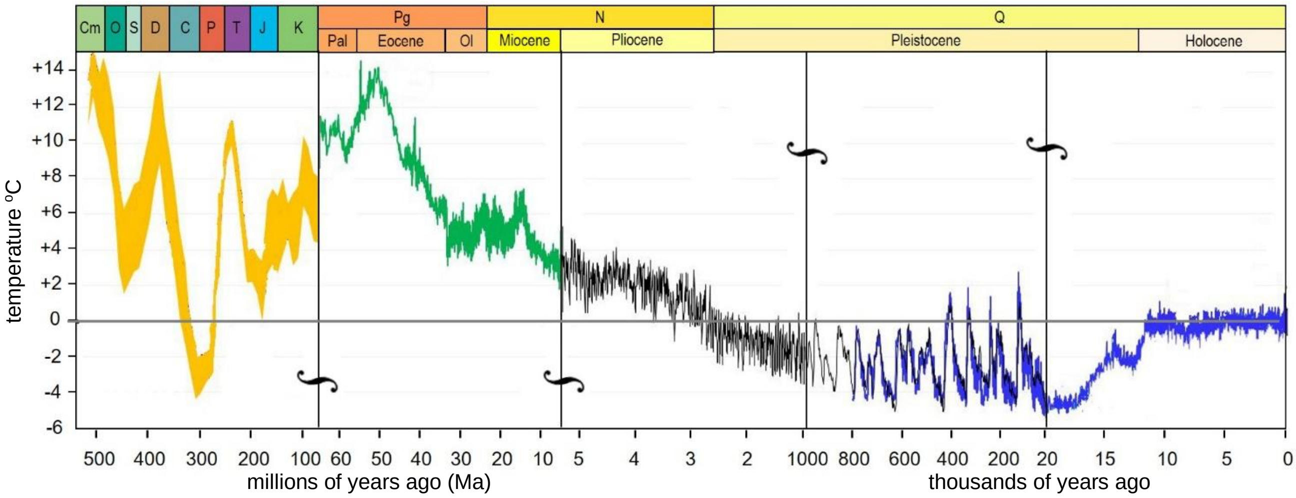
Figure 4.56. A hang glider buoyed up by thermals over the Mam Tor ridge, Derbyshire

At an even smaller scale, smoke rises because it is carried upwards by rising warm air currents above fires. Conversely, if you stand at the foot of a glacier on a calm day you will feel eddies of cold sinking air from the glacier flowing down around you.

4.3.3 Atmospheric change

Evidence from several different sources shows that the mean temperature of the Earth's surface has changed greatly in the past. Figure 4.57 has five graphs showing how temperature is thought to have varied above and below the 0 on the graph, corresponding to today's mean surface temperature of 14°C. The first graph shows temperature change from 540Ma to 65Ma ago, the second from 65Ma to 6Ma, the third from 6Ma to 1Ma, the fourth from 1Ma to 20,000 years ago and the final graph for the past 20,000 years.

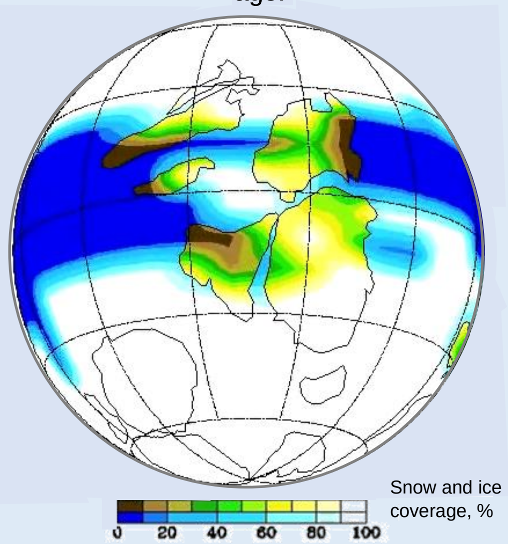
Figure 4.57. The past mean temperature of the Earth's surface (°C) as shown by evidence from several indicators. Five graphs are plotted, end to end, showing change over shorter and shorter lengths of time, up to the present day. The zero (0°C) on the graphs is today's mean Earth temperature of 14°C.



The graphs show that in the geological past mean highest temperatures were more than 10°C above today's temperature (sometimes more than 14°C); the lowest were down to 5°C below today's. At today's temperatures the poles are glaciated, showing that when temperatures were lower in the past, glaciations must have been much more widespread. The graphs show widespread glaciations or **icehouse conditions** in the Pleistocene and Carboniferous/Permian periods. There is also evidence of icehouse conditions in the Ordovician/Silurian periods and of two glaciations in Precambrian times, before the start of the graphs in Figure 4.57. The later Precambrian ice age was the greatest that the Earth has ever experienced; the whole Earth may have been ice-covered (so-called '**snowball Earth**') or a zone of open sea may have remained near the Equator ('**slushball Earth**').

Box 4.14. Snowball Earth or slushball Earth?

The snowball Earth theory is based on evidence that between 650 and 635Ma sedimentary rocks deposited by ice sheets covered continents that palaeomagnetic measurements show were near the Equator. This idea would be strengthened if it could be shown that all sedimentary deposits that formed at that time were glacial. But this is very difficult to prove, since there are no fossils available to date the sedimentary rocks laid down then (as life with hard parts had not yet evolved and would not normally be found in glacial deposits anyway). There is also sedimentary evidence that there were at least some areas of open water at the time. So many Earth scientists are happier with a slushball Earth idea (with open water in seas near the Equator) than the snowball Earth one. Nevertheless, there is good evidence that the Earth experienced a very severe glaciation around 640Ma ago.



Computer simulation of ice coverage during Snowball Earth

One of the processes that is thought to have triggered worldwide glaciations is positive feedback from the albedo effect, described in section 1.3 of this book. As the ice sheets grew they reflected more and more of the Sun's radiation, cooling the Earth and causing more ice sheet growth, until much of the planet was covered by ice.

The end of this severe ice age may have been triggered by volcanoes pumping large amounts of carbon dioxide into the atmosphere, causing large-scale warming through the greenhouse effect.

Between the very cold periods, there were times when Earth was much warmer than today, particularly in the Palaeocene/Eocene, the Permo-Triassic, the Devonian and the Cambrian periods. These times, when there were no global ice sheets, are often called 'greenhouse conditions'.

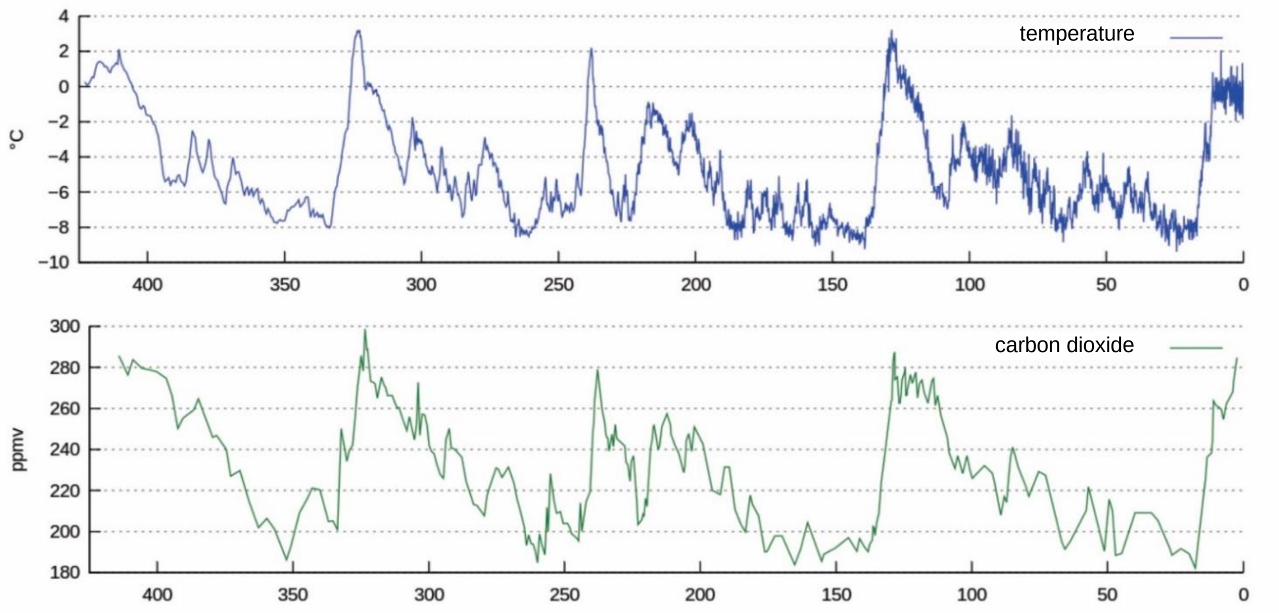
Figure **4.58.** Extracting an ice core from a core tube taken from an ice borehole

Over geological time, the overall energy reaching Earth from the Sun has been increasing, so we might expect global temperatures to show a steady increase too. Since there has been no steady increase in Earth's mean temperature, other factors must be having an effect.

Ice cores give clues to the main factors affecting Earth's temperature. Boreholes are drilled into the thicker parts of polar ice sheets to extract cores of ice (Figure 4.58). Data from the ice cores can be used to show the temperature, as well as the content, of different gases in the atmosphere at the time when that layer of ice was formed.

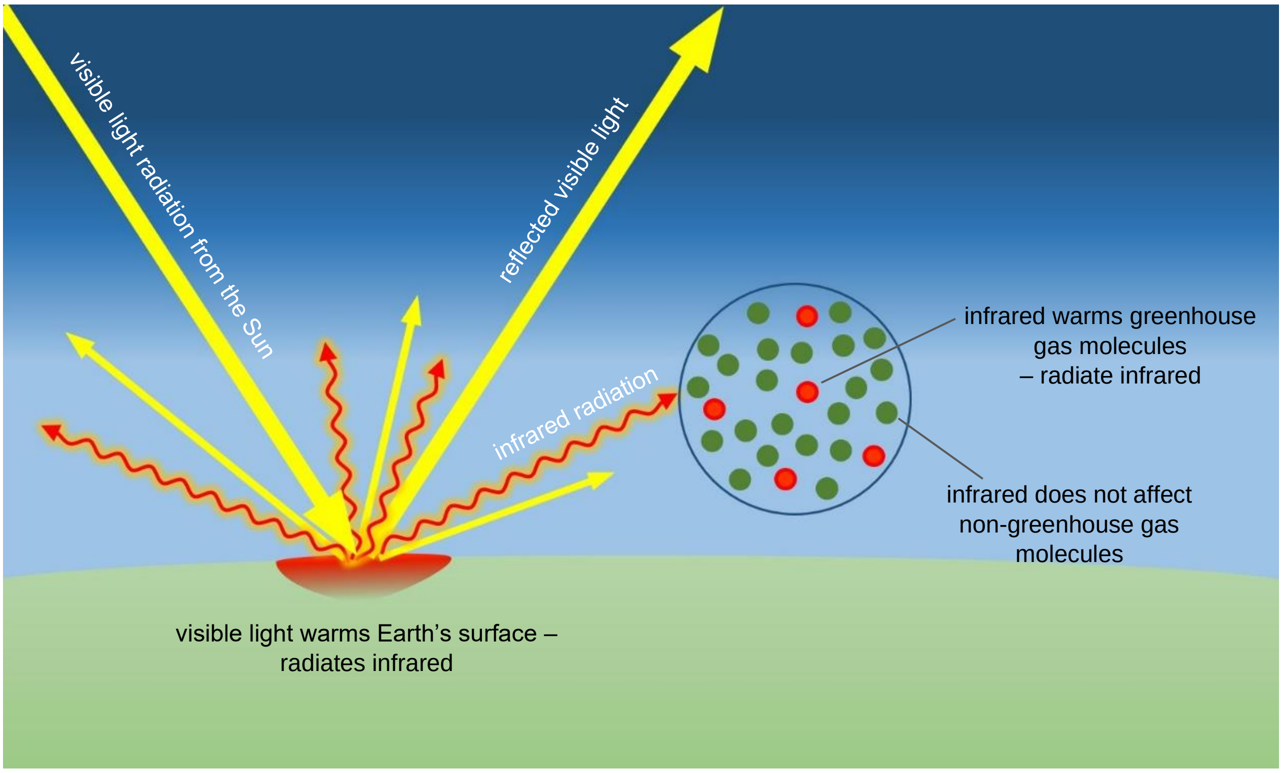
Figure 4.59 shows plots of temperature and the carbon dioxide content of the atmosphere over the past 400,000 years. The graphs show a very close connection between the amount of carbon dioxide in the atmosphere and the Earth's temperature. Whilst some Earth scientists argue that it is the temperature of the Earth that causes the change in carbon dioxide levels, most Earth scientists think the opposite, believing that changes in carbon dioxide levels cause the changes in Earth's temperature. It is therefore widely accepted that high carbon dioxide levels cause high Earth temperatures.

Figure 4.59. Graphs of the temperature change and variation in CO_2 in the atmosphere over the past 400,000 years recorded in the Vostok ice core from Antarctica (ppmv = parts per million CO_2 in the atmosphere by volume)



The link between the Earth's temperature and the amount of carbon dioxide (and other key gases) in the atmosphere is called the **greenhouse effect**, as shown in Figure 4.60.

Figure 4.60. The greenhouse effect (infrared radiation is heat)

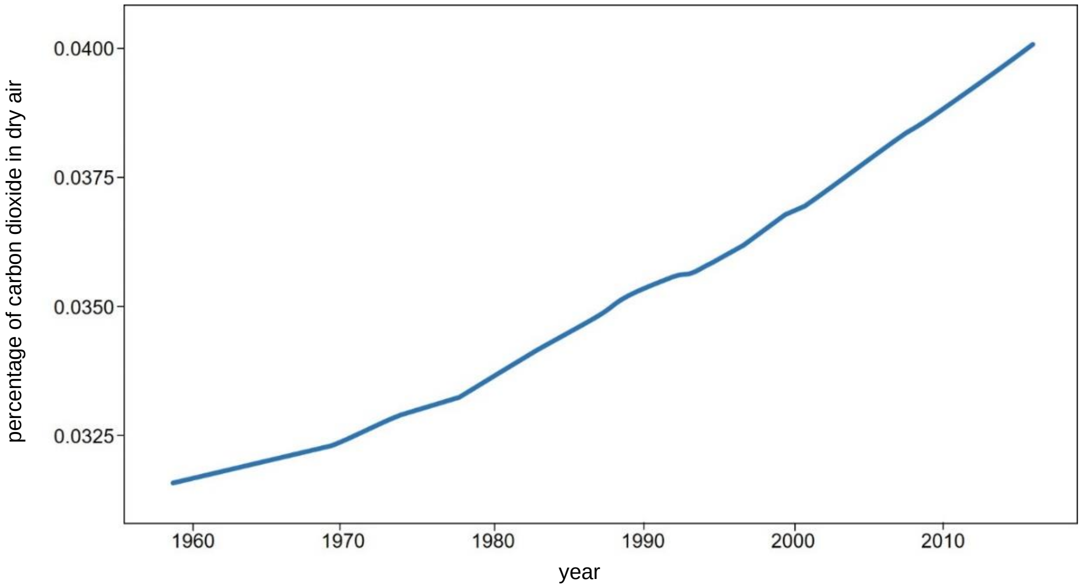


Radiation from the Sun reaches the Earth as visible light. Some of this is reflected back out into space, but some is absorbed by the Earth's surface and re-radiated as heat, or infrared radiation. Some of the re-radiated heat goes through the atmosphere and out into space, but some is absorbed by greenhouse gases, making the atmosphere warmer. The more greenhouse gas there is in the atmosphere, the warmer it becomes, warming the Earth in turn. The most abundant greenhouse gas in Earth's atmosphere is water vapour, followed by carbon dioxide, methane and nitrous oxide. The amount of water vapour in the atmosphere varies all the time and the amounts of methane and nitrous oxide are small, so that the main gas that affects the Earth in the long term seems to be carbon dioxide.

If there were no greenhouse gases in the atmosphere, all the radiation from the Sun would be re-radiated, and the Earth would be so cold that it would be permanently frozen. So we need the greenhouse effect for the Earth to be warm enough for life. The problem comes when extra greenhouse gases are added to the atmosphere causing the **enhanced greenhouse effect.** It seems that the very warm periods of Earth's past (greenhouse conditions) are linked to high levels of greenhouse gases in the atmosphere. These may be linked to active plate tectonic periods causing increased volcanic activity, releasing the greenhouse gases.

Climate change therefore seems to be closely tied in to the amounts of greenhouse gases in the atmosphere. This is why scientists are concerned that the amount of carbon dioxide in the atmosphere is increasing. The amount of carbon dioxide in the atmosphere has been monitored from the observatory on top of the quiet volcano Mauna Loa, in Hawaii, since 1958. These measurements show the steady rise seen in Figure 4.61.

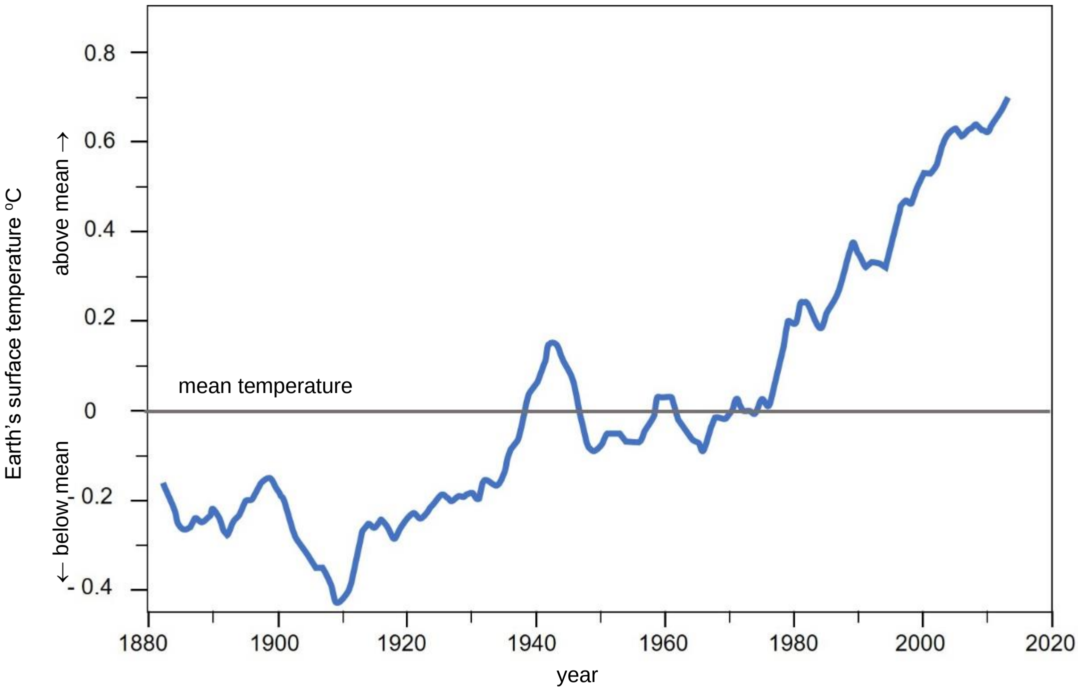
Figure 4.61. The change in carbon dioxide levels in the atmosphere since measurements began in 1958, measured from the Mauna Loa observatory, Hawaii. (The top of Mauna Loa was chosen as the site for these observations because it is high in the atmosphere and far from continental land masses; the measurements are not related to any volcanic activity.)



Most scientists think that this recorded steady rise in the carbon dioxide content of the atmosphere is mostly due to humans burning fossil fuels like coal, oil and natural gas, together with the large-scale deforestation of tropical rainforest areas. The burning of fossil fuels releases extra carbon dioxide into the atmosphere and the destruction of vegetation leaves fewer plants available to remove and store carbon dioxide through photosynthesis. While we know that the oceans can absorb some of the extra carbon dioxide from the atmosphere, scientists are continuing to research how much can be absorbed and how this might affect the oceans.

This steady increase in the carbon dioxide content of the atmosphere seems to be linked to the fairly steady rise in the Earth's temperature measured since the 1960s, shown on the graph of data compiled by the National Aeronautics and Space Administration (NASA) in the USA, shown in Figure 4.62.

Figure 4.62. Change in the Earth's surface temperature, from data compiled by NASA



So, as carbon dioxide in the atmosphere increases, most probably due to human activity, the Earth is becoming warmer. A warmer Earth might seem like a good idea to those people who live in colder countries, but a steadily warming Earth might cause great problems, as envisaged in Table 4.25.

Table 4.25. Problems likely to be caused by a warming Earth

Potential problem	Likely effect
A 'tipping point' may be reached (as described in Section 1.3) where positive feedback loops cause the Earth to become very much warmer	All the problems in the table below would be much greater
Warmer oceans contribute more heat to the atmosphere	Oceanic heat drives storms, so that the Earth could become much more stormy
Warmer conditions increase rates of evaporation and condensation	Water cycle changes mean that some areas of the planet become wetter and others drier
Land-based ice caps melt, adding water to the oceans	Sea level rises cause extra flooding of low-lying areas, particularly during storms
The ocean waters expand as they warm	Expansion of ocean waters contributes to sea level rise
Rising sea levels reduce the area of land available for agriculture and industry	Mass migration of human populations may occur, seeking more favourable land in already crowded areas of the world
Warming of oceans affects the volume and speed of ocean currents with effects on the oceans and atmosphere	Ocean currents redistribute heat on Earth; change of these currents may make some regions warmer and others colder
Climatic belts move towards the poles	Movement of climatic belts causes some species to flourish in new areas, but others to die out
Ocean water becomes more acidic as it dissolves carbon dioxide	Species such as corals that cannot adapt to more acidic waters die out, together with their coral reef communities

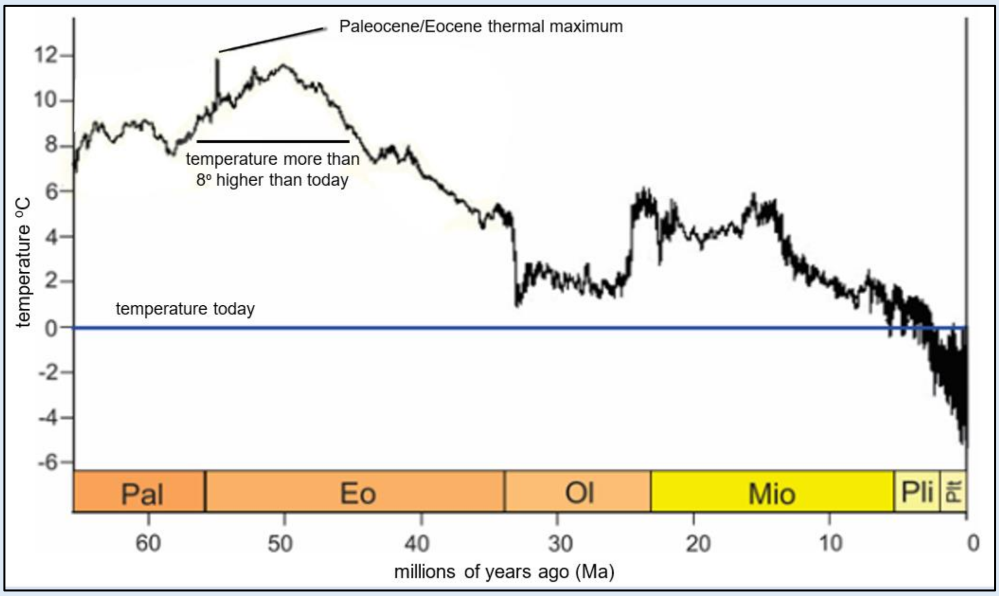
There may be some advantages in a warming Earth, such as the possibility of growing new crops in areas nearer the poles, increased forest growth encouraged by the additional carbon dioxide, and the Northwest sea passage north of northern Canada becoming viable for shipping in the summer. However, most people would argue that the disadvantages strongly outweigh possible advantages.

The Earth has been subjected to strong global warming in the past, as during Palaeocene/Eocene times, and has survived. However, the survival of humans and a wide range of other species in those conditions is very doubtful.

Box 4.15. The Earth during the Paleocene/Eocene thermal maximum

During the greenhouse conditions at the boundary between the Paleocene and early Eocene periods, some 56Ma ago, there is evidence that the Earth was up to 12^{o} warmer than today and remained more than 8^{o} warmer for nearly 10 million years. This was probably linked to huge amounts of carbon dioxide being released into the atmosphere at that time. Geoscientists are very actively researching this high temperature period, because it might shed some light on current climate change studies.

Box 4.15. The Earth during the Paleocene/Eocene thermal maximum, continued



Temperature of Earth (°C) compared with today's temperature, over the past 65 Ma

There were no ice sheets on Earth at this time and the expansion of the warm ocean contributed to the rise in sea levels that drowned many low-lying continental areas. Fossil evidence shows that forests covered the whole Earth, from the equator to the poles, apart from a few drier areas. Tropical rainforests grew in North America and Europe and palm trees grew in the Arctic. New mammal species evolved, but mostly these were very small dwarf species, probably because smaller mammals are better adapted to hot conditions than larger animals. Reptiles were abundant, particularly pythons and turtles. Insects were common. There were major changes in the oceans. Whilst many bottom-living microscopic species became extinct, planktonic organisms near the sea surface flourished. The warm oceans teemed with fish and other sea life. This was a very different world from the Earth today.

Graphs of Earth's temperature, particularly over the past million years, as shown in Figures 4.57 and 4.59, show regular cycles of temperature change. These are thought to be linked to the amount of the Sun's radiation received by the Earth, due mainly to regular changes in the way the Earth spins and orbits the Sun. However, modern greenhouse effects may have even more impact than these regular changes caused at the time.

4.4 Biosphere

The more we study life on Earth, the more we discover how biosphere processes are very closely interlinked with those of the other spheres, the geosphere, hydrosphere and atmosphere. We have also discovered how small changes in one part of one of these systems can produce large changes elsewhere.

4.4.1 Evolution

William Smith had shown that fossils in rocks were always found in the same sequence (see Section 3.2) but scientists did not know why this happened. In 1858 a theory explaining why fossil sequences changed in this way was put forward by Charles Darwin and Alfred Russel Wallace; this is the theory of evolution.

The theory of evolution is based on three scientific observations about the biosphere:
1) individual organisms (such as animals, plants, fossils) are different from one another;
2) some individuals are better adapted to survive and reproduce than others; and
3) many of the features of individuals are passed on from one generation to the next.

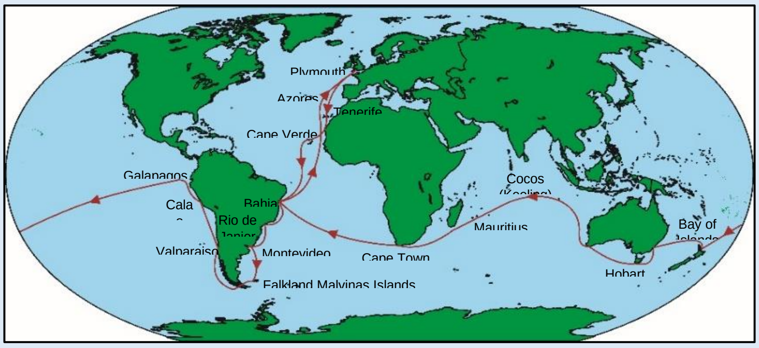
These resulted in a process that caused groups of animals and plants to change over time, or to evolve, which Darwin called **natural selection**. This was later called the 'survival of the fittest', where the organisms best fitted for survival produce offspring, whilst those less well fitted, die out. Evolution was, for the first time, able to explain most of the huge numbers of observations that had been made about life on Earth.

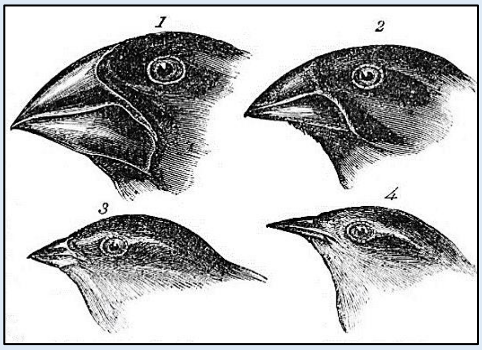
We now know how the three scientific observations of evolution can be explained:
1) individuals differ from one another because sexual reproduction causes each individual to have a unique set of genes;
2) some combinations of an individual's genes give it a better chance of survival than others; for example, some gene combinations might give an animal longer legs, allowing it to run faster; other gene combinations might cause a tree to have a thicker trunk, allowing it to grow taller;
3) during sexual reproduction in plants and animals, half of the genes come from one parent and half from the other; the half of the genes received from one parent carry some of the parent's features onto the next generation.

Evidence from the fossil record shows that some types of life seem to evolve steadily, whilst others show one group suddenly evolving into a different group. Sudden evolutionary jumps seem to occur where a group of animals or plants is separated from the rest of its group, for example on an island or on top of a range of mountains. In these conditions, when a plant or animal develops a new feature, it is not lost by interbreeding with other mainstream individuals but can be preserved and developed down the generations.

Box 4.16. Charles Darwin and evolution

In 1831 Charles Darwin joined the exploration voyage of the *HMS Beagle* sailing ship as a naturalist, a scientist studying both geology and biology. During the round-the-world voyage of nearly five years, Darwin recorded enormous numbers of observations of the geology, fossils and wildlife of the countries he visited and collected many specimens. Some of the birds he collected from the Galapagos Islands in the eastern Pacific Ocean were later shown to be types of finch. These birds had become adapted to different lifestyles on different islands with special adaptations to their beaks to allow them to eat nuts, fruit or worms. Darwin reasoned that probably one species of finch had originally reached the islands from mainland South America, but that, as they moved to different islands, they became isolated and so evolved differently into distinct species. This and similar observations were an important trigger to his thinking on evolution.





After the voyage in 1839, Darwin published his book of observations, including his studies of volcanic rocks and his experience of an 8.5 magnitude earthquake in Chile. It was not until 20 years later, in 1859, that he published his book on the theory of evolution, called '*On the Origin of Species*'.

Box 4.16E. Evolution triggered by pollution

The pale-coloured peppered moth used to be the most common type in the Manchester area of northern England, because it had excellent camouflage on the bark of trees. However, when trees became blackened with soot during the industrial revolution, the dark-coloured variety became common instead. Later, as pollution decreased, the pale-coloured version became the most common form again.

At the time when the theory of evolution was still being debated, after Darwin's death, English schoolteacher James Tutt presented the peppered moth as a case of evolution by natural selection. This provided strong support for Darwin's theory.

Chris King

The different distributions of continents resulting from plate movement have had important effects on the evolution of life on Earth. When all the continents were together in a supercontinent, there were few isolated land areas and so few possibilities of an evolutionary jump. Meanwhile, around the coasts of the supercontinent the shallow sea areas were interconnected again, also reducing opportunities for evolution.

At other times, when continents were separated, evolutionary jumps occurred on the separate land masses and in the separated shallow seas. An example is the evolutionary changes which have given New Zealand such a unique mixture of wildlife.

Figure 4.63. Map of the continents at 280Ma, during Permian times, with a supercontinent joining land areas and interconnected shallow seas (slower evolution)

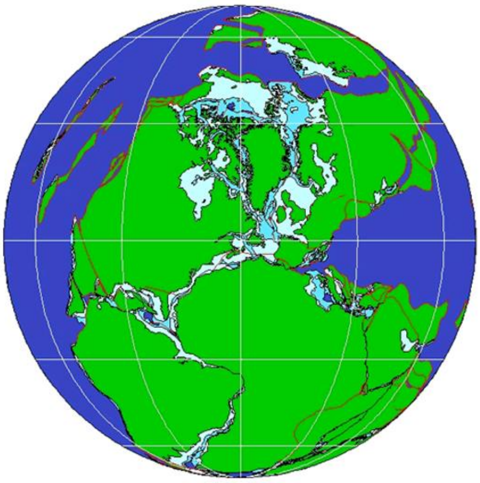
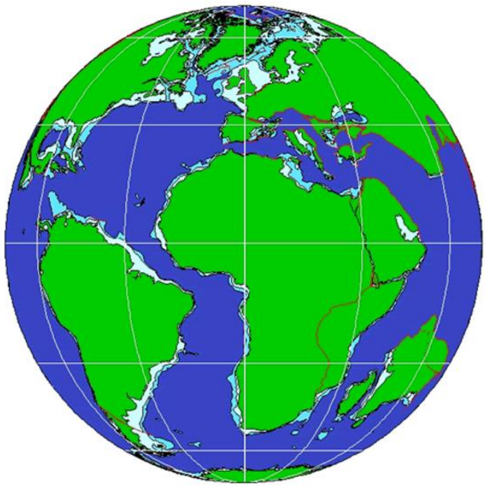
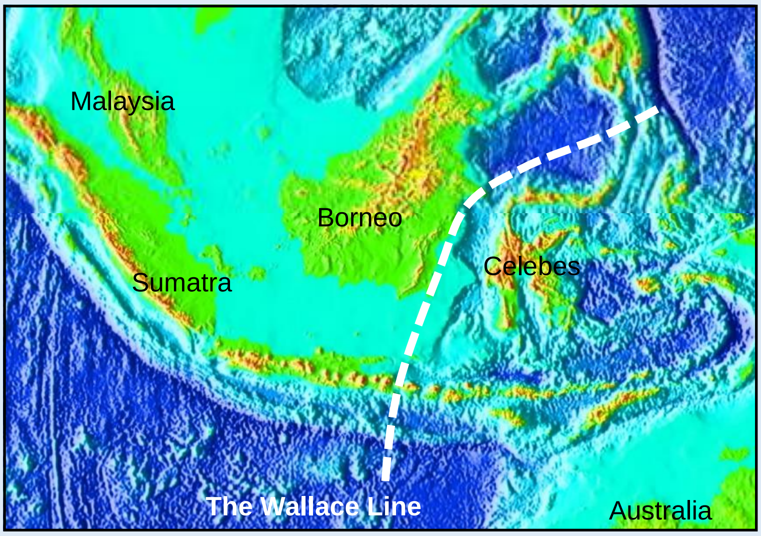


Figure 4.64. Map of the continents at 85Ma, during Cretaceous times, with separated continents and shallow seas (faster evolution)



Box 4.17. The Wallace Line

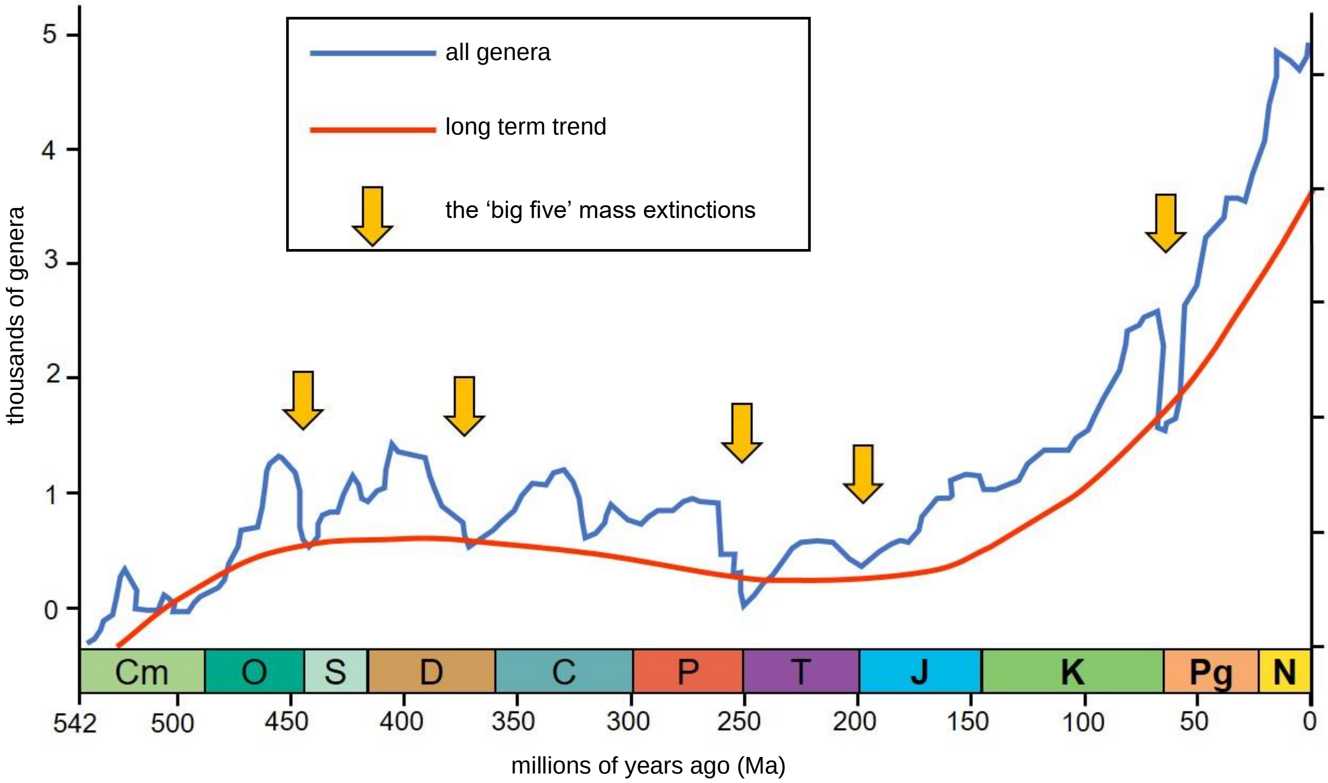
Alfred Russell Wallace, who with Charles Darwin co-developed the theory of evolution, put together his ideas during his wide travels, first in the Amazon area of South America and later in south-east Asia. He identified the line in south-east Asia, now called the Wallace Line, which separates largely Asian animals to the west from a mixture of Asian and Australasian animals to the east. This prompted him to think about how these different groups of animals could have first formed, and so led him to develop the theory of evolution. When Australasia was separated from Asia in the geological past, different groups of animals evolved in the different regions.



The global rock sequence records several episodes of **mass extinction**, when many different groups died out at the same time. Indeed, the boundaries of each of the main geological periods since the Cambrian were defined where a mass extinction event caused major changes in the fossil record. Usually, before a mass extinction event, life seemed to be progressing normally. Then at the event, a wide range of groups suddenly died out. After the event, those groups that survived evolved into a series of new groups, probably because there was no competition from the groups that had died out. So, as well as causing the extinction of many groups, mass extinctions also triggered the later evolution of many new groups.

In the past 450 million years, there have been five major mass extinctions when more than 60% of all species died out, but the greatest was at the end of the Permian period when more than 90% became extinct.

Figure 4.65. The long-term trend of life on Earth and the major extinctions, as shown by the number of genera (biological groupings containing numbers of species)



Many different theories have been put forward to explain mass extinctions; these include huge volcanic eruptions, global falls in sea level, impacts by asteroids and major changes in climate (cooling and warming). Sometimes several of these events, together with other major changes, seem to have happened at the same time.

Box 4.18. The 'great dying' mass extinction

At the end of the Permian period (and the start of the Triassic) at 252Ma, more than 90% of all species on Earth died out. Up to 96% of all marine species became extinct, with major extinctions of land animals and insects too. The devastating conditions during this mass extinction are almost impossible to imagine – not only did so much animal and plant life become extinct on land, but in the oceans too, when 'nearly all life died'.

Many ideas have been proposed to explain this 'great dying', including the extrusion of huge volumes of basalt lava, which happened at the time of the extinction and would have released enormous amounts of ash and volcanic gas into the atmosphere. The ash would have blocked out sunlight, stopping photosynthesis, whilst the release of volcanic carbon dioxide would have caused global warming and acidification of the oceans.

The mass extinction may have been triggered by an asteroid hitting the Earth, but if this was so, and the impact site was in the oceans, the site would probably have disappeared by now, as the ocean floor is recycled by plate tectonics. However, no other evidence of a major impact seems to have been preserved from that time either, so an asteroid collision explanation for this event seems unlikely.

Glossopteris tree leaves and seed pods – found before the 'great dying' event, but not afterwards

Box 4.19. The K-Pg mass extinction

At 66Ma, the end of the Cretaceous and the beginning of the Paleogene periods, three-quarters of life on Earth became extinct. No large amphibians, large reptiles (including the dinosaurs but not including crocodiles), or large mammals survived. Marine groups were also devastated; the ammonites became extinct, together with many fish, shark and plankton groups.

The conditions at the time must have been devastating, with so many plants and animals on land and in the sea dying out over a very short time.

A range of scientific ideas has been suggested to account for such a sudden dramatic event, including the enormous volcanic eruptions of the Deccan Traps basalts (in what is now India), sea level rise, climate change or a combination of these.

When it was discovered in the 1980s that the K-Pg boundary is marked in many rock sequences by a layer of muddy sediment rich in the element iridium, the idea was proposed that an asteroid hit the Earth; asteroids are rich in iridium but the Earth is not. Soon afterwards the Chicxulub crater was discovered in the Gulf of Mexico in Central America. This 180 km wide, 20 km deep crater is thought to be the impact site of an asteroid at least 10 km across. Extra impact evidence is given by 'shocked quartz' (quartz crystals deformed by sudden pressure) and beads of glass (tektites) of rocks melted and ejected by the collision. Scientists are almost certain that an asteroid collision caused the crater, but whether that collision caused the K-Pg mass extinction, or contributed to it, or had little effect on life on Earth at the time, is still being hotly debated.

The K-Pg mass extinction left a lot of habitats almost empty, giving opportunities for a sudden burst of evolution after the extinction event. Birds, fish and mammals in particular evolved into many new groups; mammals developed into horses, bats, whales and primates.

Box 4.19. The K-Pg mass extinction

Tyrannosaurus rex – one of the last dinosaur groups found before the K-Pg mass extinction

Geologists collecting sediment at the K-Pg boundary, Wyoming, USA

The Cretaceous/Paleogene mass extinction is often called the K-Pg mass extinction because, in the geological column, the Cretaceous period can be abbreviated to 'K' (the letter 'C' had been used further down the column for 'Carboniferous') and the Paleogene is abbreviated to 'Pg' (since 'P' had been used previously for the 'Permian' period) (Figure 4.65). Confusingly, the K-Pg mass extinction used to be called the K-T mass extinction before the T ('Tertiary') was subdivided. One of the subdivisions became called the 'Paleogene' and the term 'Tertiary' is no longer formally used.

The mass extinctions have had not only bad but good effects too, since each mass extinction left new habitats available for new bursts of evolution. So, without extinction in general and mass extinction in particular, evolution might not have produced the huge diversity of life on Earth today.

4.4.2 Impact on other systems

It seems that the more we study Earth's systems, the more we discover the vital effects that life has on those systems. The biosphere has had major effects on the evolution of the whole planet.

For example, the weathering of rocks involves a range of processes. Freeze-thaw and heating and cooling have physical effects of breaking up rock into smaller pieces. Plants also have many physical effects, from the rootlets of lichens forcing apart grains of rock, to the movement of the roots of trees in storms levering boulders away from rock faces. Similarly, the chemical effects of acidic rain and oxidation in the chemical breakdown of rocks is increased by the life in soil adding extra carbon dioxide to rain, making soil water even more acid and able to attack rock. Rotting organic matter also produces acid, adding to the acid content of the water, with a range of other biochemical breakdown effects as well. Soil only forms where there is life which adds plant material and soil animals. Thus where there is little life, such as in polar land areas or dry deserts, there is no soil.

Life also plays a key role in rock building, as well as rock weathering, as shown in Table 4.26. Some 10% of all rocks found at the Earth's surface are limestones, and most of these result from biological processes. Life is therefore very important to rock-formation.

Life has also produced all our fossil fuel supplies. Coal is formed as described in Table 4.26 and during its formation releases natural gas, or methane. Oil is formed mainly by the breakdown of tiny planktonic plants and animals deposited in sea floor muds and later buried.

Table 4.26. The contribution of life to rock-formation

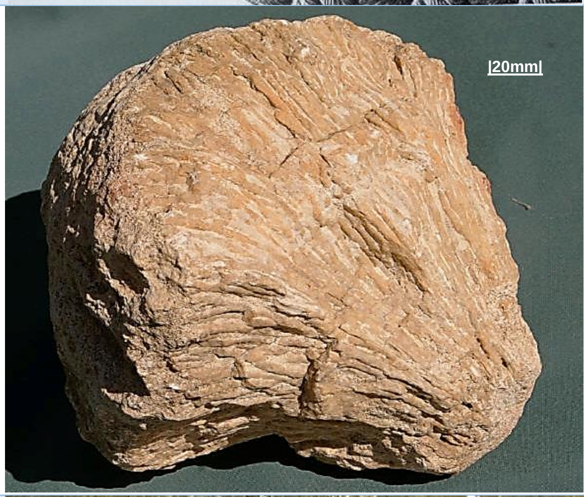
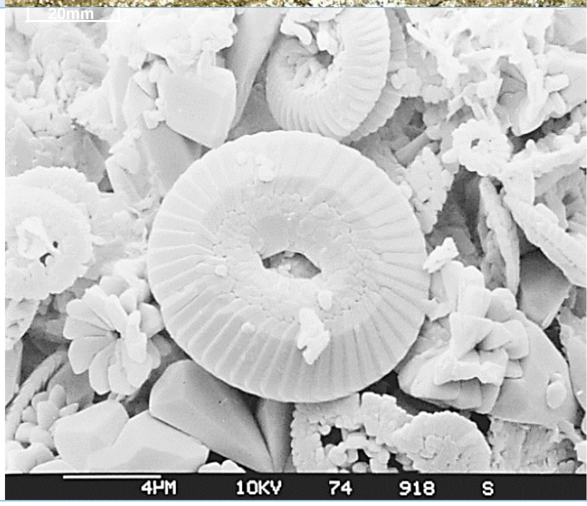
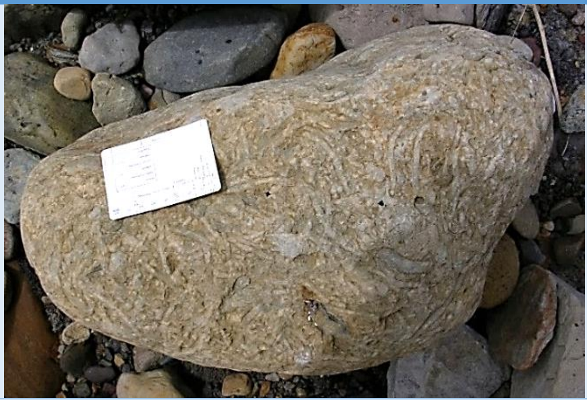
Process	Description	Image	Source
Coal-formation	When there is abundant plant life and the plants die, they do not completely decay if they fall into an environment without oxygen; first they form peat and later, through burial, coal		Leaf fossils in Carboniferous coal
Reef-formation in limestone	Corals and other animals build reefs today and have also been major reef-builders in the geological past; they are important contributors to limestone-formation		*Cladophyllia* reef coral, Middle Jurassic age, Wiltshire
Limestones formed of fossil debris	Most limestones are formed of fossil debris. The fossils are sometimes easy to see, as in this specimen, but can also be broken into tiny fragments, impossible to see by eye alone		Limestone of brachiopod shell fragments. National Stone Centre, Wirksworth, Derbyshire
Chalk – very fine-grained limestone formed of coccoliths	Before scanning electron microscopes (SEMs) became available, geologists had little idea of how chalk formed. Now SEMs have shown chalk is made mainly of coccoliths, the tiny calcium carbonate platelets of planktonic algae, together with other microfossils		A scanning electron microscope image of coccoliths; these make up the very fine carbonate mud which can eventually become chalk

Table 4.26. The contribution of life to rock-formation , continued

Process	Description	Image	Source
Sediments changed by burrowing	Animal burrows in many sandstones and mudstones have destroyed the original bedding and other structures		Burrows in a boulder of Jurassic limestone, Burniston, Yorkshire coast

The balance between the storing of carbon in limestone formation, and its release through weathering, probably played a key role in the geological past, through the amount of carbon dioxide in the atmosphere and the resulting greenhouse effect. The subduction of limestones at convergent plate margins may also have played an important role in the climates of the geological past too, through the breakdown of limestone to form carbon dioxide, later released as volcanic gases.

Box 4.20. The Gaia hypothesis of James Lovelock

James Lovelock has proposed not just that life plays an important role in Earth systems, but that it controls Earth systems. He has called his idea the Gaia hypothesis (after the Greek Mother Earth goddess, Gaia) and argues that, in the same way as your body has lots of different systems to regulate it, so does the Earth. For example, if you get too hot, you sweat to cool yourself down, but if you get too cold, shivering warms you up. When scientists did not agree that the Earth could have systems to regulate its temperature and other aspects of its systems, Lovelock devised a computer programme that he called 'Daisyworld' to show how this might work.

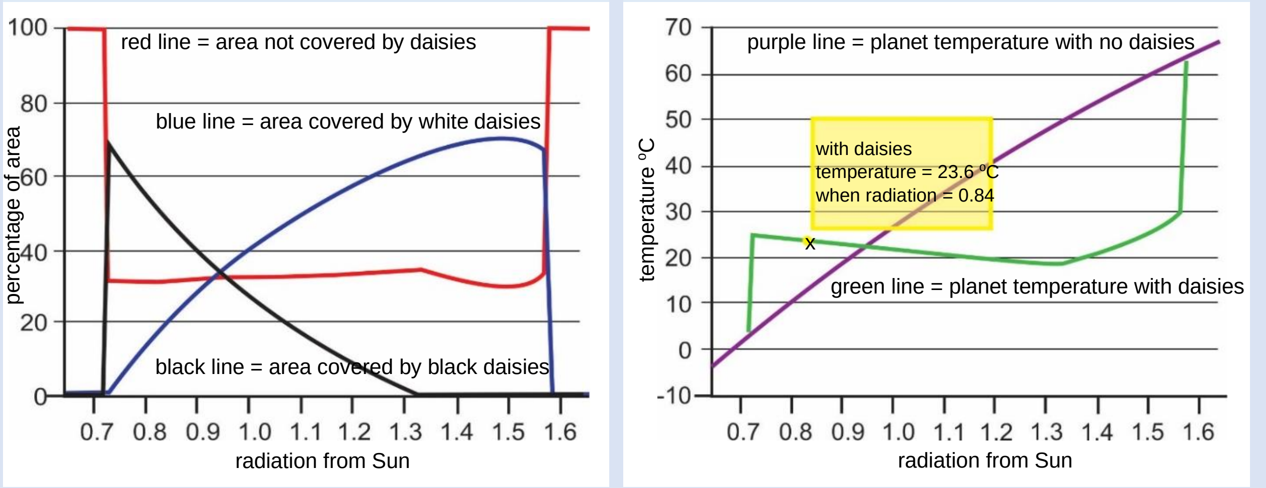
In the simulation shown in the graphs, the brown line in the right-hand graph shows how the temperature of his simulated planet, if it had no life, would increase as radiation from the sun increased. Lovelock's simulated planet is similar to the Earth, where radiation received from our Sun has been steadily increasing over geological time.

If, in the early days of the simulated planet, a large area was covered by black daisies (black line on the left-hand graph), the black colour would have absorbed more radiation and increased the planet's temperature to more than 20ºC – the green line on the right-hand graph. Then, as the radiation from the sun increased, it became too hot for the black daisies and they began to die off, becoming steadily replaced by white daisies (blue line on the left-hand graph). As more and more radiation was received from the sun, more and more was reflected by the white daisies, keeping the temperature to near 20ºC. In the end, the daisies could no longer cope and died out. Then the temperature of the planet dramatically increased to what it would have been if it had had no daisies at all. So, the effect of the daisies has been to keep the simulated planet at a fairly steady temperature as the solar luminosity (radiation from the sun) more than doubled.

Through this simulation, Lovelock demonstrated how evolving life could regulate the temperature of a planet. He reasoned that, in different ways, life could regulate the systems of a whole planet like the Earth, maintaining its capacity for life, from the time when abundant life first evolved until now.

Box 4.20. The Gaia hypothesis of James Lovelock, continued

Some of Lovelock's thinking now underpins how scientists investigate Earth systems, although many do not agree that life does regulate the whole Earth system in the way that Lovelock describes.



5 Earth's system produces resources

Natural resources are all the materials of the geosphere, hydrosphere, atmosphere and biosphere which can be used by humans. They include the wide range shown in Table 5.1.

Table 5.1. Natural resources from the Earth

Source	Some of the natural resources extracted for use	Image	Source
Geosphere	• Soil • Bulk rocks for construction and industry • Ancient evaporite minerals • Metal ores • Fossil fuels • Geothermal energy • Uranium		Reclaiming an old sand and gravel pit Cheadle, Staffordshire – smoothing out the old deposits and tree-planting
Hydrosphere	• Drinking water • Water for industry and agriculture • Evaporite minerals • Hydroelectric, wave and tidal energy		Watergrove water supply reservoir, Wardle, Rochdale, Greater Manchester
Atmosphere	• Gases of the atmosphere • Air for industry • Wind for power		Membrane oxygen plant, used to extract oxygen from the air
Biosphere	• Fish and other marine creatures • Trees • Products of farming on land and in the sea		Fishing boats, Beer, Devon

5.1 Raw materials and fossil fuels

All raw materials and fossil fuels that are extracted from the ground have first been naturally concentrated. This natural concentration happens in one of two ways: either natural processes have concentrated the material itself, or natural processes have removed the other non-economic materials, leaving the useful materials behind.

Materials are only extracted for use if they are economically viable. This means that a material is extracted only if the balance between the local or global need for the material (the demand) and its local or global availability (the supply) makes the price high enough. If the price is high enough to cover the prospecting, extraction and remediation, processing and transportation costs, then the material is worth extracting.

All development to meet human needs should be sustainable. **Sustainable development** has been described as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs." This means that economic and population needs should be met without damaging the environment so badly that future needs cannot be met. For the extraction of natural materials, all aspects of the operation should be sustainable.

Remediation involves extracting the material with the least possible damage to the surrounding community and environment, and returning the area afterwards to near its original quality, with monitoring so that later problems do not occur. Some countries have high levels of environmental control, ensuring proper remediation, whilst other countries have lower levels of control.

5.1.1 Bulk raw materials for construction

Large-scale construction needs huge quantities of material, and this can be very costly to transport. This is why many superquarries are sited on the coast and other major quarries have their own train lines. Most towns and cities have nearby quarries to supply their construction needs, well connected by roads. The crushed rock and sand and gravel from some quarries is used as construction **aggregate**.

Table 5.2. Examples of bulk raw materials used in construction

Bulk raw material	Details	Image	Source
Igneous rock	Igneous rock like granite, gabbro and dolerite, is very tough and used for aggregate in concrete, road construction and the crushed rock ballast on which railways are laid		Quarrying Precambrian igneous rock at Bardon Hill, Leicestershire
Limestone	Limestone is used for aggregate and cement-making		Carboniferous limestone quarries, Buxton, Derbyshire

Table 5.2. Examples of bulk raw materials used in construction, continued

Bulk raw material	Details	Image	Source
Sand and gravel	Sand and gravel are extracted for aggregate in concrete		Sand and gravel pit in the Thames Valley, Thorpe, Surrey

Box 5.1E. Building stones in England

The varied geology of England has resulted in the use of a wide range of building stones down the centuries. Before the 1800s, inland transport links were poor, so local stone was used, giving regional variation in building materials and styles of construction. Most of England to the south and east of the line joining the rivers Tees and Exe is underlain by sedimentary rocks, so sandstones and limestones are the most common. An exception is the Charnwood Forest area of Leicestershire, where ancient igneous rocks and slates are found at the surface.

In southwest England, the granites and slates of Devon and Cornwall have been used locally, and the granite has also been exported, mostly by sea, to London. Igneous rocks in the Lake District are mostly used within the region, but the green slates, from the metamorphism of volcanic ash, have been more widely used as roofing slates. Although slate is the best natural roofing material, thin-bedded sandstones and limestones have been used locally and are referred to as “stone slates”, even though they are not metamorphic rocks.

When good transport became common, some building stones were carried far and wide, by sea, canal, rail and road. Examples include limestones: Portland, Bath, Beer and Lincolnshire Limestones, and dolomitic limestone. Sandstones range from the red sandstones of Devonian and Permo-Triassic age to the coarse “Millstone Grit” and the finer-grained sandstones of the Carboniferous Coal Measures. These include “York Stone”, quarried in Yorkshire and Lancashire (not at York!) and even carried at one time by canal and then by sea to London for large scale paving.

Most quarries excavating building stone have closed and it is now quite difficult for conservation architects to find sources of stone for matching older buildings.
Large blocks of stone are mostly quarried using a small amount of black powder explosive, to loosen the rock along natural joints, but without cracking the stone. In some limestone quarries, the blocks are sawn out from the face instead. In rare cases the stone is (or was) mined underground.

Once taken to the workshop, the stone is cut into shape using a variety of saws, mostly diamond saws that contain tiny industrial diamonds.

Carboniferous sandstone block, split away from the face by the plug and feather method (two metal wedges are forced apart by hammering in a third wedge, the plug).

Granite ruined pumping house and gatepost, Cornwall

Box 5.1E. Building stones in England, continued

Quarry face with sawn bocks of limestone being extracted – the Permian Magnesian Limestone at Cadeby quarry near Doncaster, Yorkshire

Carboniferous sandstone walls and ‘stone slates’, Haugh Lane, Sheffield, Yorkshire

Delabole slate quarry, Cornwall

Devonian-age Delabole slates used for roofing and walls, Tintagel, Cornwall

Peter Kennett

Box 5.2E. The Box stone mines

Box stone mine with an old block crane

The Georgian Circus at Bath, Somerset (1754-68)

According to legend, St Aldhelm, Abbot of Malmesbury (c. 639-709) threw his glove down on Box Hill, saying, "dig here and you will find treasure". The treasure was the creamy, oolitic, Jurassic limestone – Box stone.

The limestone occurs in nearly horizontal strata towards the top of the hills around Box village, 6 miles (9.7km) from Bath, Somerset. Originally it was dug out from the hillside though horizontal tunnels known as adit mines. It has been used in the area since Roman times and was found in the archaeological investigation of Box Roman Villa.

Box 5.2E. The Box stone mines, continued

The stone was used in the late 1100s and early 1200s for local abbeys and great houses. As the transport of stone improved, first by the building of canals and, later by the arrival of the railway, Box stone began to be used even more widely. The railway made transport much cheaper, and the excavation of the famous Box railway tunnel in 1841, by Isambard Kingdom Brunel, revealed vast beds of high quality stone. Much of this was used for the Georgian buildings in Bath. The peak period for quarrying was between 1880 and 1909 when millions of tonnes of stone were cut from Box and at the hills around Bath. The underground quarries (also known as mines) have many miles of interconnecting passages. The quarries in Box continued working until 1969.

Elizabeth Devon

5.1.2 Bulk raw materials for industry

Industry requires bulk raw materials for a range of uses, including: making building materials, supplying the ceramic industries, and as the raw material for the chemical and agricultural fertiliser industries (Table 5.3). Since transport costs for bulk materials are high, either the processing plants are sited as near to the quarries as possible, or good transport links are needed. They are called *bulk* raw materials because their cost is low related to their large mass and volume, so that to be profitable they need to be excavated in bulk at large scale.

Table 5.3. Examples of bulk raw materials used in making building materials, the ceramic and chemical industries

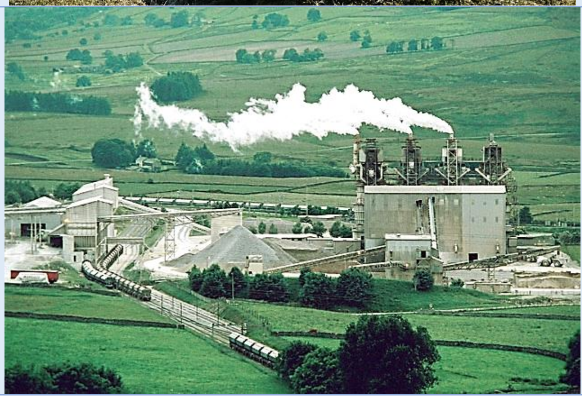
Bulk raw material	Details	Image	Source
Limestone	Cement for concrete; cement blocks and mortar are made by heating limestone and clay together in a kiln and grinding up the result with gypsum		Cement works, Hope Valley, Derbyshire
	Limestone is heated to form quicklime used in agriculture and in the chemical industries to make steel, coatings for paper, bleach, in refining sugar and for water treatment		Hardendale modern lime kilns, Shap Fell, Cumbria

Table 5.3. Examples of bulk raw materials used in making building materials, the ceramic and chemical industries, continued

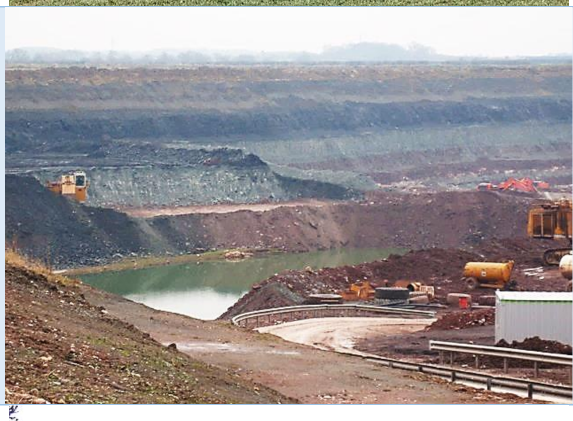
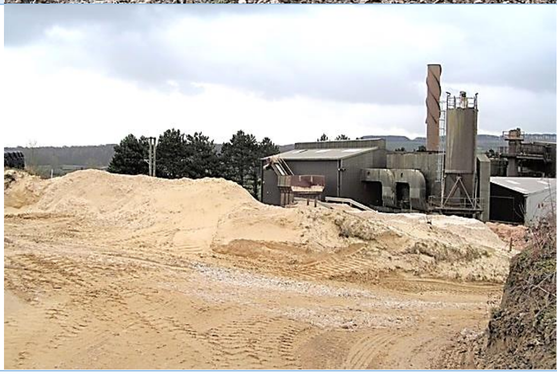
Bulk raw material	Details	Image	Source
Salt	Sodium chloride is not only recovered by evaporation in salt ponds, but is also mined underground from ancient halite deposits; it is used for salting food, de-icing roads and in the chemical industry for plastics and paper-making		Historical image of Witton Hall Rock Salt mine, Northwich, Cheshire. English towns with the ending 'wich' were salt-mining towns. The rock salt is Triassic in age
Potash	Potash is potassium chloride and is recovered by mining and brine pumping. It is the main source of potassium in agricultural fertilisers. It is also used to produce a wide range of industrial chemicals		The surface workings of the Boulby deep potash mine in North Yorkshire. The potash deposit is Permian
Gypsum	Gypsum, the calcium sulfate mineral, is quarried and heated to make plaster of Paris, which is used to make the plaster and plasterboard wall coverings used in most modern buildings		A gypsum quarry in Triassic rocks near Nottingham
Brick clay	Brick clay is moulded into brick shapes and then fired in kilns to produce household bricks for building		Brick clay in the old Neepsend Brickworks quarry in South Yorkshire; Carboniferous age

Table 5.3. Examples of bulk raw materials used in making building materials, the ceramic and chemical industries, continued

Bulk raw material	Details	Image	Source
China clay	China clay is used to make fine porcelain china, and in paper-making and cosmetics		Wheal Martyn china clay pit near Treverbyn, Cornwall; excavation machinery in the distance for scale
Silica sand	Silica sand is mixed with soda (sodium carbonate), lime (calcium oxide) and other chemicals, melted and then floated on molten metal to make the glass used in today's windows		Silica sand quarry near Kennythorpe, North Yorkshire

Box 5.3E. Limekilns

Lime has been important for centuries, being used to make lime mortar for building work, as white lime washes for covering walls and for spreading onto acid soils to improve their fertility for agriculture. Today, it is widely used in the chemical and steel industries, in glass making, food processing and in agriculture.

Lime is produced by heating limestone with coal (or previously with charcoal). Carbon dioxide is given off as the limestone (mostly $CaCO_3$) changes to quicklime (CaO). Quicklime is used for making specialist mortars, but it can cause burns and is usually converted to safer slaked lime ($Ca(OH)_2$) by adding water, before it is transported for sale.

Old limekilns occur across the English countryside, wherever limestone was exposed, where fuel was available to heat the kilns, and wherever there was a local demand from farmers or builders. Even in limestone districts today, farmers still add lime to their fields, because rainwater washes it out, making the surface soil acid and less fertile.

As transport improved in the 1800s, lime-making moved nearer to limestone areas with good transport links, such as canals, railways and the coast. Lime could then be made on an industrial scale, as it is today.

Box 5.3E. Limekilns

Old limekiln on Kepworth Moor,
near Northallerton, Yorkshire

Disused limekiln near Wells, Somerset

An industrial scale limekiln beside the former mainline railway near Millers Dale, Derbyshire. The kiln built in 1880 was closed in 1944. It produced 50 tonnes of quicklime per day

Peter Kennett

Box 5.4E. Cheshire salt and the UK's largest rock salt (halite) mine

Rock salt is the rock made of the mineral halite. Its chemical name is sodium chloride (NaCl). Halite precipitates when water evaporates. The salt beds in Cheshire formed about 200 million years ago during Triassic times when the Cheshire Basin, a deep, sedimentary basin, formed by tectonic movements in late Carboniferous times, was flooded by a shallow sea. At this time, the area was closer to the equator and had a hot, arid climate. Salt lakes (playas) and tidal flats formed in the desert environment in the basin. Layers of mud and silt were deposited and, as the shallow waters of the playas and tidal flats evaporated, layers of salts, including halite were also deposited. As the sedimentary basin continued sinking during the Triassic, the cycle of flooding by the sea followed by periods of evaporation was repeated several times so that great thicknesses of mudstone, siltstone and salts built up.

The halite formations in Cheshire are the source of 90% of the UK’s salt. Cheshire salt has been exploited since early times. It was originally extracted from brine springs, hand-dug brine pits and wells. In the late 1700s, wind- and steam-powered brine pumping started wherever brine could be found underground. This extraction process unfortunately resulted in subsidence of the land surface above. Salt mining developed in the 1800s and, during the 1900s, controlled brine pumping was introduced to reduce the chance of surface subsidence. Enormous salt cavities are now engineered by this brine pumping method to store natural gas underground.

Box 5.4E. Cheshire salt and the UK's largest rock salt (halite) mine, continued

UK's largest rock salt mine is in Winsford, Cheshire, and it is one of only three places in the UK where rock salt is commercially mined. The Winsford Rock Salt Mine is claimed to be 'Britain's oldest working mine'. Salt is extracted at depths of about 140 m. Machines, known as electric-driven continuous miners, cut out walls of salt leaving 'rooms' or chambers with pillars of rock salt supporting the roof. This extraction method is called 'room and pillar mining' and as much as 25% of the rock salt is left underground as pillars. The rock salt is crushed before being transported by conveyor belts to the surface. Most of the salt produced in this mine is used to treat frozen roads.

The Cheshire mine has a constant temperature and humidity. It is also dry and free of gases and this makes it useful as a storage location. Spaces left behind after extracting the rock salt can be 8m high and 20m wide and are used to store the National Archives, film archives and bank records. Even Crossrail uses the mine's archive division, known as Deepstore, to keep rock samples taken from boreholes drilled as part of the Crossrail construction.


Winsford Rock Salt Mine in Cheshire. The southern end of the covered conveyor, where salt is tipped into a domed store


Brine pump near Warmingham, Cheshire; one of many pumps used for brine extraction

Maggie Williams

Box 5.5E. Glassmaking in St Helens, Lancashire

The way we make glass today has not changed much since it was first produced in ancient Persia (called Iran today) and Egypt. Glass is a silica glass made by the melting of quartz (SiO_2) in a furnace with limestone (calcium carbonate, $CaCO_3$) and soda ash (sodium carbonate, Na_2CO_3). The melting temperature that the sand needs is very high, around 1700°C. This process in industrial glass plants, produces soda-lime-silica glass, the general-purpose glass we commonly see around us. This glass is transparent or translucent and isotropic, meaning that it has the same properties in all directions.


The Palm House at Royal Botanic Gardens, Kew, London, built between 1844 and 1848, the first glasshouse to be built on this scale. There are 16,000 panes of toughened glass in the building

Box 5.5E. Glassmaking in St Helens, Lancashire, continued

To make different types of glass, commercial glass manufacturers use slightly different glass-making processes. This can simply be by adding other chemicals to change the appearance or properties of the finished glass. For example, chromium- or iron-based chemicals are added to the molten sand mixture to make green-tinted ('bottle-green') glass. Mixing in cobalt salt produces blue glass. The addition of boron oxide makes oven-proof glass and lead oxide produces crystal glass.

Large, clear plates of glass are made by the "float glass" process. This method was pioneered in the 1950s and involves pouring molten glass onto a pool of molten tin, giving very flat, clear, uniform sheets. This manufacturing process is named after the pioneer British glass manufacturer Pilkington.

The best glass silica sands are those which are well sorted sediments. The main source rocks are quartz sand, sandstones which have a silica cement, and metamorphic quartzite. One of the reasons why St Helens in Lancashire developed as a major glassmaking centre is that large parts of the area around St Helens are covered by deposits of wind-blown sand. These sands are up to 3m thick and, lying immediately beneath a cover of topsoil, are easy to excavate. The sands are fine-grained and have a uniform composition and grain size. The sand used for glass making, mainly from the top 0.5 to 1m directly below the topsoil, contains 97% SiO_2 and only between 0.1% and 0.12% Fe_2O_3 and so produces a clear glass rather than a green-tinted glass. The sands are mostly medium- to fine-grained sand, ideal for glassmaking. Later, sand from the Cheshire Basin was used instead because the St. Helen's area sands are so thin that large areas of land were required.

Metropolitan Cathedral of Christ the King, Liverpool. This piece of artwork, made of hand-cut, mouth-blown glass, is one of several stained-glass columns created by the German artist Raphael Seitz

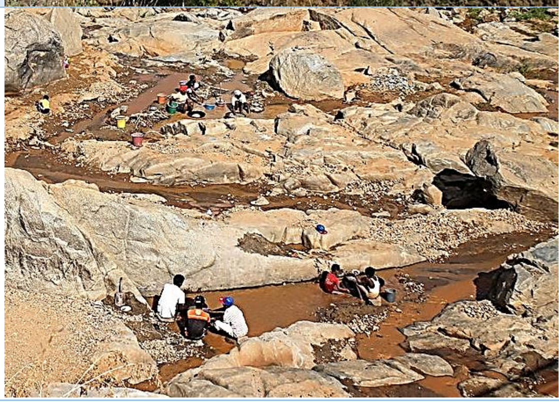
St Helens developed as a glass making centre because it not only had supplies of sand for making the glass, but also had coal supplies to fire the glass furnaces. It also had good communications and so, from the late 1600s onward, benefited from the rapid growth of the nearby city of Liverpool, a ready market for glass.

Maggie Williams

5.1.3 Metal ores

Metal ores are natural concentrations of metal that are economically valuable. They need even more concentration than do bulk raw materials, to make mining economic. A range of sedimentary, igneous and metamorphic processes naturally concentrate ores, and some examples are included in Table 5.4.

Table 5.4. Examples of metal ore extraction

Metal ore	Natural concentration	Image	Source
Iron, Hematite, Fe_2O_3	The enormous banded ironstone sequences in Australia and in other continental areas were formed in Precambrian times, by sedimentary processes that scientists are still trying to explain		Tom Price ironstone mine, Western Australia – everything in the view is stained red by hematite dust
Copper, chalco-pyrite, $CuFeS_2$	Chalcopyrite and other copper minerals were concentrated by hot hydrothermal watery fluids that originated deep below the surface, through metamorphic and hydrothermal processes		Bingham Canyon copper mine, Utah, USA – the largest mine in the world, at more than a kilometre deep and four kilometres wide
Lead, galena, PbS	Lead ore is often found with zinc, copper and silver ores; the ores are often concentrated by the hydrothermal fluids produced when magmas intrude the surrounding rocks		Mt Isa mine, Queensland, Australia; the high chimney is for the lead smelter; the copper smelter chimney is red-white
Gold, native gold, Au	Gold can be found native, un-combined with any other element; since it is a dense mineral, after it is released from rock by erosion, it can be deposited as placer gold in the beds of streams		Commercial gold panning by the Sakalava people in Madagascar

Box 5.6E. Mining iron ore in England

Iron ores have been mined in England since pre-Roman times, when small-scale smelting and forging industries were found across the country. Most iron ores in England are sedimentary, mainly the minerals siderite ($FeCO_3$) and limonite ($2Fe_2O_3.3H_2O$). They occur either as nodules scattered throughout mudstones and shales, or as layers interbedded with these rocks.

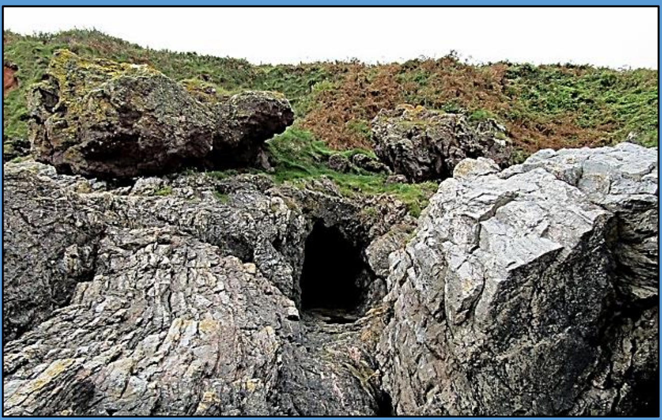
In Tudor times, the Weald of East Sussex, Surrey and Kent was the major centre of English iron production, using local Cretaceous iron ores. Local charcoal was used for smelting and water power for working furnace bellows and forge hammers.

Once Abraham Darby had perfected the use of coke (made from coal) for smelting, in the late 1700s, production moved to coalfield areas where “clayband” ores and the more carbon-rich “blackband” ores were interbedded with the Coal Measure rocks. Then, iron- and steel-making centres developed rapidly in centres like the Black Country in the West Midlands and across the coalfields of northern England.

Later, sedimentary ironstones composed mostly of oolitic limonite and chamosite (an iron silicate) were extracted from sedimentary Jurassic rocks in Northamptonshire, Lincolnshire and the North York Moors. Although low-grade (around 25% iron content), these were excavated using large-scale opencast methods and resulted in the growth of centres like Corby, Scunthorpe and Teesside.

Haematite (Fe_2O_3) is a much richer ore, averaging 48% iron, and occurs as replacement deposits in the Carboniferous Limestone of Cumbria and north Lancashire, and in parts of Devon, giving rise to an iron and steel industry in those regions. However, the deposits are small by world standards and are expensive to mine, so the haematite is no longer worked.

Most large-scale iron and steel production in England finally became concentrated on the coast, using imported high-grade ores, with the remaining inland centres focussing on special steels, such as Corby for manufacture of tubes, and Sheffield for stainless steel and heavy forgings.



Horizontal tunnel (adit) of the Sharkham Point iron mine near Brixham, Devon, which mined hematite ore until 1915

A walking dragline extracting sedimentary iron ore near Scunthorpe in the 1980s

Peter Kennett

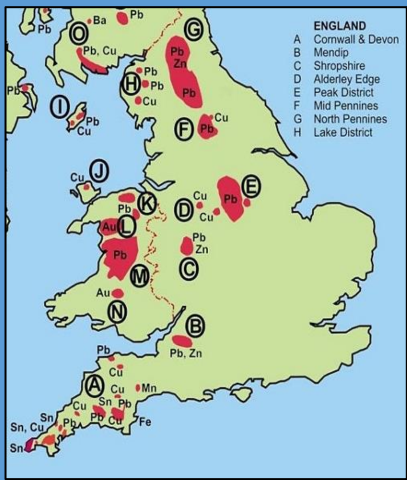
Box 5.7E. Mining lead ore in England

Magpie Mine, Sheldon, Peak District, Derbyshire

Galena and barite in a brecciated limestone, Hucklow Edge Vein, Peak District, Derbyshire

Lead ores have been worked in England since at least Roman times, as shown by the Latin inscriptions on Roman ingots of lead. In England the lead mining industry became very important in the 1600s and 1700s, but declined rapidly in the late 1800s as foreign sources became cheaper. Today, lead ores are only produced in England as a by-product in the processing of fluorite in the Peak District, but the legacy of mining is very clear in the landscape of most old lead mining areas. Lead is used today for flashings for roofs (to seal the joints between different parts of the roof), batteries, and for shielding against ionising radiation.

The main ore of lead is galena (PbS), which may react with groundwater to produce other ores such as cerussite ($PbCO_3$). Galena occurs in hydrothermal mineral veins. The ores were carried dissolved in hot water from below, and then crystallised in the cooler environment of cracks in the host rocks above, gradually growing outwards from the walls of a joint or fault in the rocks, intermixed with other minerals.



The main lead ore fields

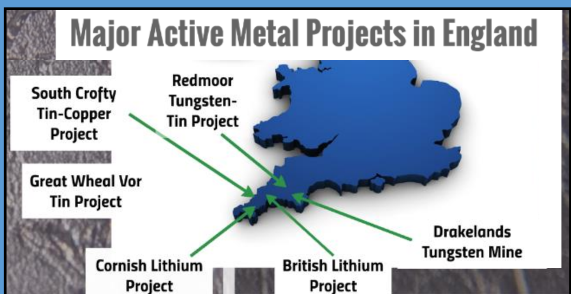
In Devon and Cornwall, the ores of lead and other metals are linked to large granitic intrusions and the heat source of the hydrothermal fluids was probably the granitic magmas. In the Pennine Hills, which were the richest lead sources in England, and in the Mendip Hills, the ore minerals are mostly found in Carboniferous limestone and sandstone host rocks. The original source of the lead in these areas is thought not to have been a nearby granite, but the deeply buried sediments which became heated by the Earth's geothermal gradient, enough to dissolve the tiny quantities of metallic minerals scattered throughout the rock.

Peter Kennett

Box 5.8E. Metal mining prospects in England

There are currently no active metal mines in England but there are several metal mining prospects in South West England – for tin, copper tungsten and lithium.

However global prospecting statistics today show that for every 100 finds of valuable resources, only about ten move onto the next stage of mining feasibility studies and these usually result in only one active mine. So prospecting remains very financially dangerous.

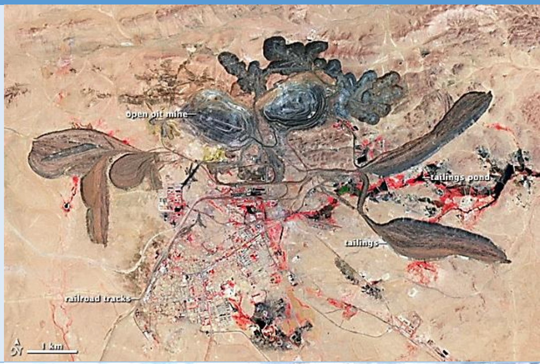


Chris King

5.1.4 Industrial minerals

These are minerals mined for their value, which are not fuel, metal ores or bulk raw materials. They include a very wide range of materials. Two examples are included in Table 5.5.

Table 5.5. Examples of industrial mineral extraction

Industrial mineral	Detail	Image	Source
Rare earth minerals	These deposits contain rare earth elements which are used in modern devices such as computer memory, mobile phones, DVDs, magnets, fluorescent lighting and rechargeable batteries		Satellite view of a rare earth mine in Bayan Obo, China
Diamonds	Diamonds from deep in the mantle are brought to the surface by volcanic eruptions which drill pipes up to the surface; they are used as gemstones and for industrial cutting and grinding		The Mir mine, Mirny, Russia

5.1.5 Fossil fuels

Fossil fuels are the remains of plants and microscopic plants and animals preserved in the ground. When they were alive, the plants absorbed energy from the Sun through photosynthesis. On dying, their remains built up, often in water with little or no oxygen. Since oxygen is required for organic material to completely break down, the remains only partially decomposed, forming sedimentary deposits rich in organic material. When this was buried and compressed, much of the water and decomposition gases were squeezed out, enriching the organic content even more. All organic materials contain the element carbon, and it is the burning of the carbon in fossil fuels that releases energy.

5.1.5.1 Peat and coal

Peat is the build-up of partially decomposed plant material in the oxygen-poor waters of bogs, marshes and swamps. The peat builds up over thousands of years, often to thicknesses of more than 2m. Peatlands are not only rich in carbon, but also capture the carbon dioxide released during decomposition, and so are one of the important stores of carbon removed from the atmosphere. If peat is buried and compressed it preserves an even greater concentration of carbon.

Peat is cut for burning and to produce organic compost for gardens. However, as scientists have understood more fully how peatland plays such an important role in removing carbon from the atmosphere, the excavation of peat has been reduced globally.

Figure 5.1. Commercial peat extraction, Bolton Fell, Lancashire

If peat were buried to even greater depths, compression by the overlying sediments would convert it to coal. However, most coal is produced in the rain forest conditions of tropical swamplands. Plants and trees grow fast in the warm wet conditions and, when they die and fall into the oxygen-poor swamps, they only partially decay. If the area is subsiding, many metres of organic material can build up, sometimes preserving leaves, roots or whole tree trunks. When the organic layer is buried steadily deeper by overlying sediments, the temperature naturally rises while water and decomposition gases are squeezed out, producing coal seams. The greater the increase in pressure and temperature, the more gas is released and the higher quality the coal becomes; the highest quality coal contains the greatest proportion of carbon.

Surface exposures of coal were first mined at the surface long ago. Then they were followed underground through horizontal or sloping tunnels called adits, or by vertical shafts. The underground mining of coal is called deep mining, and some coalmines have reached more than 1km in depth. Deep coal mining continues in many parts of the world, but a cheaper alternative is the opencast mining of coal.

In modern opencast pits, the topsoil is removed and stockpiled. Then the sedimentary rocks overlying the coal seams are removed and stockpiled elsewhere. When the coal seam is reached, the coal is carefully cleaned, and then large-scale machinery is used to chop out the coal and transport it out of the pit. Sometimes opencasting reveals the old deep coal mining tunnels, as in Figure 5.2. Deeper and deeper opencast slots are excavated as deeper seams are extracted, sometimes to a depth of 60m. Then the next slot is excavated and backfilled with the waste rock from the previous slot. The opencast miners work across the site, slot by slot, until all the coal has been removed and the last slot filled. Then the topsoil is replaced and the area landscaped to as near its original conditions as possible.

Figure 5.2. An opencast coalmine in Carboniferous coal, Orgreave, South Yorkshire, 1997

5.1.5.2 Oil and natural gas

Much of the natural gas extracted from the Earth was produced by the natural de-gassing of coal as it was compressed and heated during burial. Meanwhile, crude oil and natural gas are formed from organic-rich mudstones and shales as they too are heated and compressed by burial. The organic material that provides the source of oil was originally microscopic marine planktonic plants and animals. These settled to the sea bed when they died and were buried in the mud that eventually became mudstone and shale. So coal and organic-rich mudstone and shale are the original source rocks of oil and gas. All the organic materials in source rocks originally obtained their energy through photosynthesis from the Sun and so they contain ‘fossilised Sun’s energy’.

For oil and gas deposits to form underground, the five things shown in Table 5.6 are required in sequence from the bottom to the top of the table.

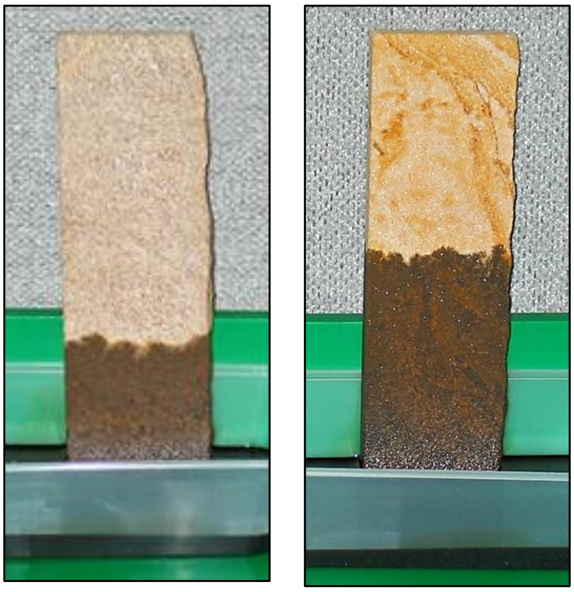
Table 5.6. The five requirements to form an oil and/or gas field

Oil/gas field requirement	Detail	Image	Source
Trap	The shape of the cap rock overlying the reservoir rock should trap a bubble-shaped body of oil or gas underneath. A common trap shape is an anticline, but there are several other types of trap as well		An anticline in Carboniferous sandstone, Upton, near Bude in Cornwall
Cap rock	Cap rocks are fine-grained rocks that are impermeable (fluids cannot flow through them) and trap oil and/or gas in a bubble shape underneath		Fine-grained Carboniferous shale, Rotherham, South Yorkshire
Reservoir rock	A reservoir rock is a rock with enough interlinked pore-spaces to contain a fluid like water, oil, or gas; it is a permeable rock which must be both porous (with pore spaces) and permeable (to allow the fluid to flow through). Sandstones are the most common oil reservoir rocks		Sandstone naturally containing oil, from the Hutton oil field in the North Sea
Burial heat and pressure	As rocks are buried, their temperature naturally rises. At about 2 km depth the temperature reaches 60ºC and organic rocks begin to release oil. By 4 km depth the temperature is 120ºC and much of the oil has been released. Natural gas begins to be released as well at this temperature. By 9 km depth, at a temperature of over 200ºC, any remaining gas becomes graphite and cannot be released		
Source rock	The source rock is the organic-rich rock from which the oil and gas originally came. For natural gas, the source rock is coal or oil sources. Most oil and some natural gas come from black organic oil shale or the organic content of large volumes of paler-coloured mudstone		Oil source rock; the Jurassic Kimmeridge Clay below Houns Tout near Worth Maltravers in Dorset

All porous rocks contain fluids in their pore spaces, usually water. As burial pressures and temperatures increase, source rocks release their oil and gas. They rise because they are less dense than the water in the pore spaces. They continue to rise through permeable rocks or along fractures, until they either reach the

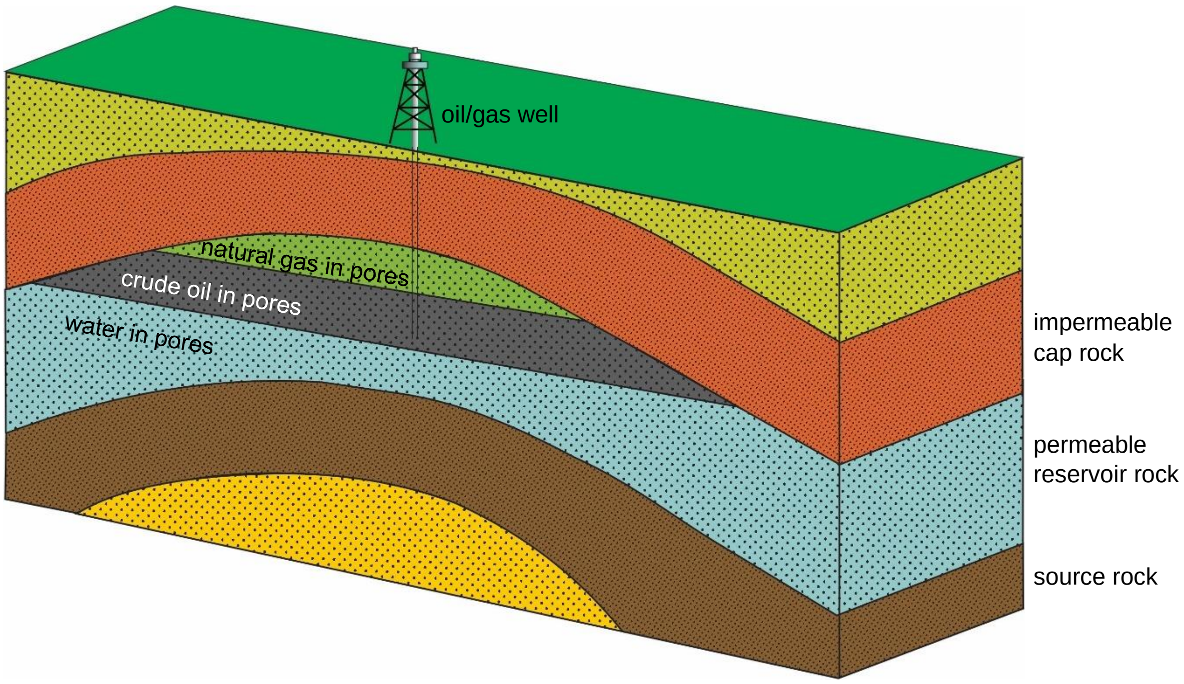
Earth's surface and are lost, or reach an impermeable cap rock layer. An underground oil/gas reservoir is formed if the cap rock is the right shape to trap oil/gas beneath, is big enough, and has a rock beneath with enough pore space to hold a good amount of oil/gas (a reservoir rock like those in Figure 5.3). The gas in the pore spaces floats on the oil, which in turn floats upon the water, as shown in Figure 5.4.

Figure 5.3. Two slabs of sandstone standing in engine oil – showing how different sandstones can absorb different amounts of oil in their pore-spaces



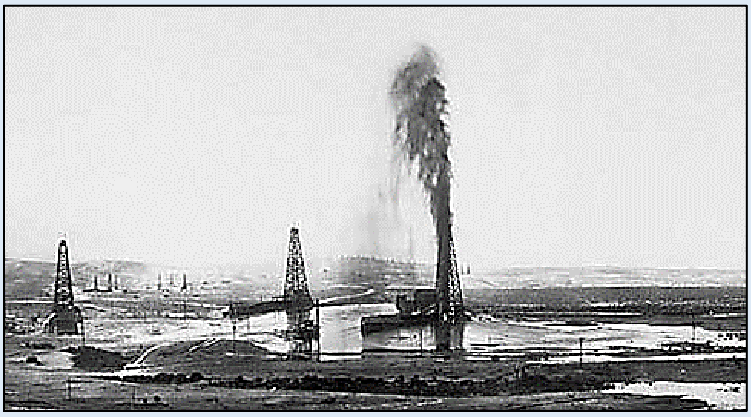
When a borehole is drilled into a trap containing oil and/or gas, the oil/gas rises up the hole because it has lower density than water and due to the pressure of overlying rocks. It can squirt dangerously out at the surface, unless it is carefully controlled by the series of valves connected to the top of all oil/gas exploration boreholes.

Figure 5.4. A trap formed of upfolded rock (an anticline) – these can contain oil, gas or both together



Box 5.1. Oil borehole valves

Oil/gas boreholes have a 'Christmas tree' of valves at the surface, to stop the naturally pressurised oil/gas from squirting dangerously out of the borehole (the image on the right is from a borehole in North Dakota, USA). In past times, before the use of these valves, oil sometimes squirted to the surface through dangerous 'gushers' as in the image below from the USA in around 1911.



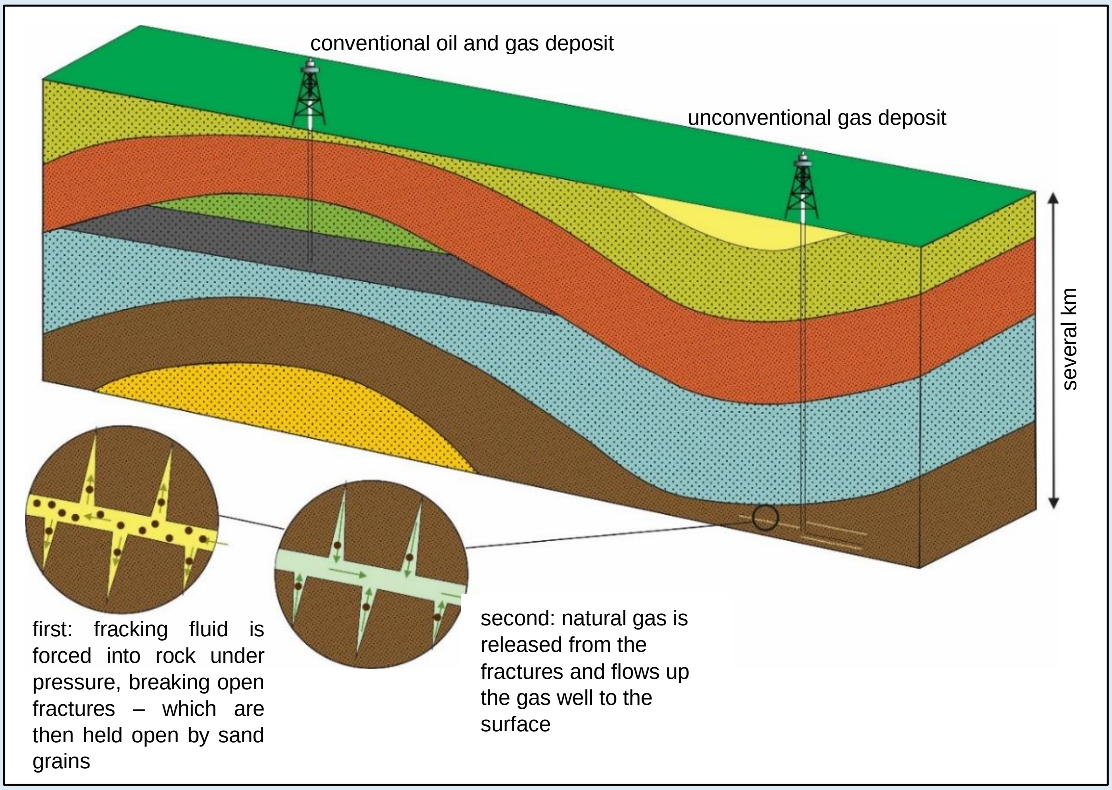
The reservoir rocks of many modern oil and gas fields are hydraulically fractured (fracked) to increase the amounts of oil/gas that can be released by the rock. During fracking, fluid is pumped into the rock under great pressure and fractures the pore spaces, so widening them. The fluid contains sand that sticks in the new fractures, holding them open. The wider pores and fractures then release oil and gas more readily.

Box 5.2. Fracking of shale and 'tight' sandstone

Fracking can be used to release natural gas from shale source rocks that have few pore spaces or have been buried so deeply that the pore spaces are small. Since economic amounts of oil/gas cannot be released from these rocks without fracking, they are often called 'non-conventional deposits', in contrast to the conventional deposits shown in the diagram. Conventional deposits have been fracked for many years.

Fracking boreholes are drilled vertically from the surface and then horizontally along the layers to be fracked. A series of horizontal boreholes is drilled from each vertical borehole. Fracking fluid is then pumped in at extremely high pressure, to counteract the mass of the rocks above. The fracking fluid is a mixture of detergent (like washing up liquid), acid of the strength of vinegar, gum (like the gum found in some sweets), water and sand. The detergent helps the fluid to slide down the hole, the acid helps the chemical breakdown of the rock and the gum thickens the fluid. The sand particles prop the new fractures open. The effect is to make previously nearly impermeable rocks permeable enough to release their gas.

Box 5.2. Fracking of shale and 'tight' sandstone, continued



If fracking is not properly controlled, the borehole casing can leak, allowing fracking fluid or gas to escape into near-surface aquifers and so pollute them. Maintaining effective leak-proof borehole casings is one of the most important controls during fracking operations and later gas extraction.

Box 5.9E. Fracking in the Fylde

In the UK, fracking started in the late 1970s in the conventional oil and gas fields of the North Sea. It has now also been used in about 200 British onshore oil and gas wells too. These include Wytch Farm in Dorset, western Europe's largest onshore conventional oil field.

Fracking only became generally known to the public in the UK in 2008, when Cuadrilla Resources was granted a licence for unconventional shale gas exploration in the Fylde, Lancashire. Natural gas had been found trapped in the microscopic pores of the Carboniferous Bowland Shale found under this part of Lancashire and much of the north of England. The Bowland Shale is thought to contain about 1,300 trillion cubic feet (Tcf) of gas.

Cuadrilla Resources carried out their first major fracking operation in 2011 near Blackpool in the Fylde, but stopped drilling a few months later, after a 2.9-magnitude earthquake damaged the borehole casing in the drilling area. Fracking is controversial in the UK because the process can cause water pollution and waste disposal problems. There is also the risk of fracking-induced earthquakes, concerns over the large volume of water required for the process and worries about air and methane pollution. Meanwhile the burning of fossil fuels has impacts on climate change. The government imposed a ban on fracking in England in 2019, followed soon afterwards by Scotland and Wales.

Fracking rig, Far Banks, Lancashire

Maggie Williams

5.1.6 Prospecting

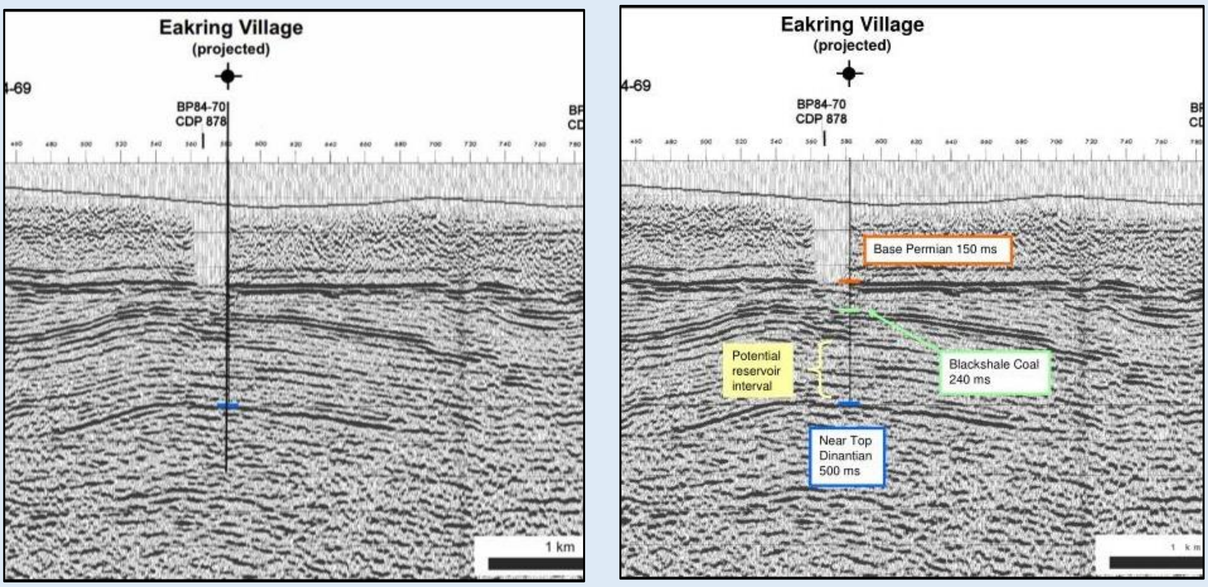
Early prospectors used to look for natural deposits of minerals or oil seeps exposed at the Earth's surface, but these surface outcrops and signs have nearly all been found, so nowadays more technical methods are needed.

Today's prospectors know from surface geology mapping on land where source rocks, reservoir rocks and cap rocks are likely to be found in the right order, so they mainly seek underground trap shapes. They may begin by flying remote sensing gravity and magnetic surveys, since these show where more dense or magnetic rocks come near to the surface and may indicate where sub-surface anticlines or similar formations occur. Then they are likely to carry out seismic surveys to show the structure of the rocks below the ground. When a likely target structure has been found, a prospecting borehole is drilled looking for oil/gas. Drilling a borehole is very expensive, particularly offshore, so the prospecting geologist must take great care in gathering information and in predicting likely targets.

Box 5.3. Seismic prospecting

Seismic surveying depends on shock waves being reflected back by different layers in the rock sequence. The exploration team makes shock waves on land by an explosion or using a 'vibration truck', or at sea by a water gun or explosion. The shock waves travel down into the rock sequence and are reflected by the different layers. The reflected shock waves are detected by a series of microphones, called geophones on land or hydrophones in the sea.

The results are analysed by computer to produce a seismic trace, as shown below. The vertical scale on the left is of two-way travel time, the time needed for the shock wave to reach the reflecting bed and to bounce back to the receiver: this indicates the depth of the bed, shown on the right. The lower diagram shows an interpretation of the seismic trace of the upper diagram, to produce a picture of the geology, like a geological cross-section.



A seismic profile, shot across the Eakring oilfield, Nottinghamshire, and its interpretation

If a seismic profile like this had been shot during oil/gas prospecting, then good targets for oil/gas might be the anticline indicated at the western end of the profile, or the rocks beneath the unconformity, if the rocks above the unconformity are impermeable.

Gravity and magnetic surveys are flown during prospecting for other natural resources too, searching for high gravity (high density) anomalies and magnetisation anomalies, as indicators of possible metal ore targets.

A prospecting method often used when searching for metal ores is geochemical stream and soil sampling. Most commonly, a series of sediment samples is collected from a streambed, dried and sieved to obtain fine-grained sediment. These are then sent to a laboratory for analysis, usually by X-ray fluorescence spectrometry

(XRF) for more than 50 elements. Where prospecting finds high levels of the target elements, the levels usually increase upstream until near their source; this is then checked by more detailed stream sampling. When the source area has been pinpointed, soil sampling is carried out on a grid pattern until the highest values are found. Finally, pits are dug until the source rock is identified and assessed for its value as a future mine site.

Box 5.4. How to find a diamond mine

- Go to a continent where diamonds have been found previously (diamonds are only formed in areas of thick, ancient continental crust).
- Carry out stream sampling and process each sample to concentrate the heavy (dense) minerals. Although diamonds are rarely found in streams, they come from unusual volcanic rocks called kimberlites and these contain other heavy kimberlitic minerals like deep red-coloured garnets.
- Send the heavy mineral concentrate off to the laboratory for analysis.
- Identify areas of streams with high levels of kimberlitic minerals and follow them to their source area.
- Carry out soil sampling on a grid pattern in the source area, concentrating the heavy minerals and sending them off to the lab for analysis.
- Find the highest kimberlitic-mineral anomaly and dig, expecting to find volcanic kimberlite.
- If you are very lucky, the kimberlite you find may be one of the very few kimberlites that contains enough diamonds to make it mineable.


Collecting a heavy mineral sample in a dry river bed


Heavy mineral jig concentrate in the field


Heavy mineral concentrate over a kimberlite


Premier diamond mine, Cullinan, South Africa

Note: sometimes when a kimberlite has been eroded in the geological past, enough diamonds can be concentrated in river or beach sediments to make them worth extracting.

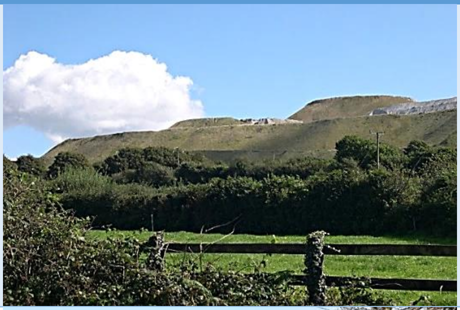
5.1.7 Environmental protection and remediation

Modern resource extraction sites usually have environmental protection and remediation policies. The environmental protection policies protect the local area from the effects of extraction. The remediation policies ensure that the site is left in a good condition after extraction ends, and that on-going monitoring of the site continues. A range of environmental protection methods is used, as in Table 5.7.

Table 5.7. Methods of protecting the environment during the exploitation of natural resources

Environmental protection method	Detail	Image	Source
Banks	Banks (bunds) are built around the top of extraction areas so that they cannot be easily seen from the outside, and to reduce dust and noise		View of a sand and gravel quarry taken from the top of the bund built to hide the site, near Four Oaks, Solihull, Warwickshire
Planting	Trees are planted around extraction sites so the site cannot easily be seen and to reduce noise and dust from the site		Screening by tree-planting near a new bund, on the left and in the background, Avon Common, Hampshire
Settling ponds	Water pumped from mines and quarries together with run-off during rainstorms is channelled into settling ponds. The mud settles out before the water is used in washing operations or allowed to flow into local streams		Poldice tin/ copper mine tailings dam and settling pond, Poldice Valley, Cornwall, now disused
Treatment of contaminated water	Waste water is treated to remove pollution before it is released into river systems		Reed bed and pond for treating drainage from an old coalmine, New Edlington, Doncaster, South Yorkshire
Vehicle washing	Mud and dust are washed from vehicles, so that they are not carried onto nearby roads		A truck wheel-washing system

Table 5.7. Methods of protecting the environment during the exploitation of natural resources, continued

Environmental protection method	Detail	Image	Source
Planting vegetation on waste tips	Vegetation is planted on waste tips so that the roots bind the soil and reduce the flow of water over the surface, thus reducing erosion		Grass-seeded terraces of china clay waste tips, Higher Coldvreath, Cornwall, England
Groundwater monitoring	A series of boreholes is drilled around the excavation site and the groundwater is monitored for pollution		Groundwater monitoring borehole near an old quarry used for landfill, near Hermitage, West Berkshire

When an extraction site closes, the site must be remediated, or cleaned up as much as possible, to make it suitable for future uses. Sometimes it is possible to return the site to its original use, but in other cases it is given over to new uses, such as a countryside park or a boating marina. The remediation processes involve landscaping the site, returning any topsoil that has been removed, and planting carefully chosen plants that will survive in the new conditions and possibly help in cleaning up the soil.

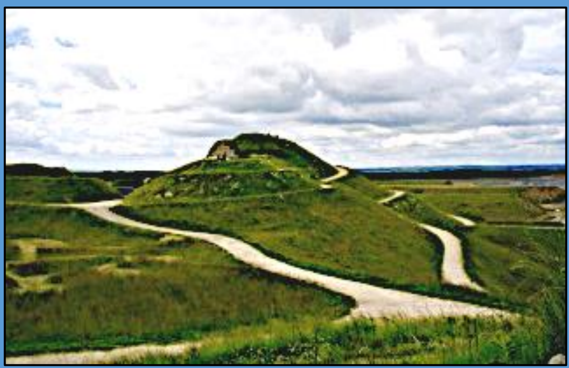
In areas of mining and quarrying, some of the old machinery and other historical items may be displayed in heritage museums. Some of the rock faces may be preserved for their scientific, educational or historical value or as sites for wildlife, such as for nesting birds or water-loving animals. Even after remediation, sites may still need regular monitoring for groundwater quality and ecology.

Table 5.8. Examples of remediation

Extraction remediation example	Detail	Image	Source
Landscaping	Quarries, pits, mines and mine waste are landscaped to reduce slopes and planted with vegetation to minimise erosion		The former Haytor granite quarry, now landscaped and turned into a country park in Devon
Reclaiming	Opencast mines may be reclaimed for agricultural use		A reclaimed old brick pit, now filled with landfill, capped and landscaped, Stairfoot, Barnsley, South Yorkshire
Preservation	Parts of the old extraction site can be preserved for their historical value		The world's oldest preserved mine engine winding house, Ecton Hill, Staffordshire
New use	The domes of the Eden project, growing plants from across the globe – sited in an old china clay quarry		The Eden Project in Cornwall
Fieldwork	Rock faces at old quarry sites have a range of scientific and educational uses		Student fieldwork at Apes Tor, an old limestone quarry, Staffordshire

Box 5.10E Opencast coalmine landscape remediation **–** Northumberlandia

Northumberlandia is a huge land sculpture in the shape of a reclining female figure, designed by artist, Charles Jencks. It was completed in 2012 near Cramlington in Northumberland. It was landscaped from a huge spoil heap (1.5 million tonnes of material) from the vast neighbouring Shotton opencast coalmine. It is 34 metres high, 400 metres long and 200m wide. Lakes have been created around the base and the figure forms the centrepiece for the new 19 hectares public park on the edge of urban Tyneside. See: https://www.northumberlandia.com/



Elizabeth Devon

5.2 Power supplies

Figure 5.5 shows how world power consumption from different sources has changed since the 1960s with power from oil, gas and renewable sources all increasing. Recently nuclear power has shown a slight decline and coal a steeper decline.

Figure 5.5. Global energy consumption; data from BP statistical review of world energy

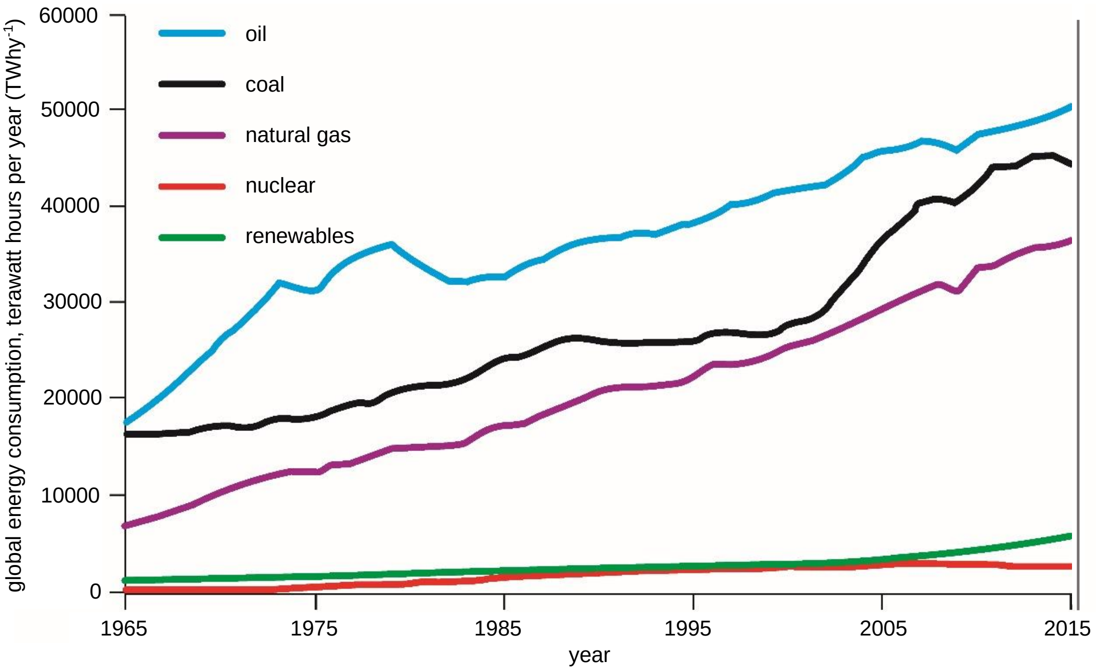


Figure 5.6. Global energy consumption; data from BP statistical review of world energy

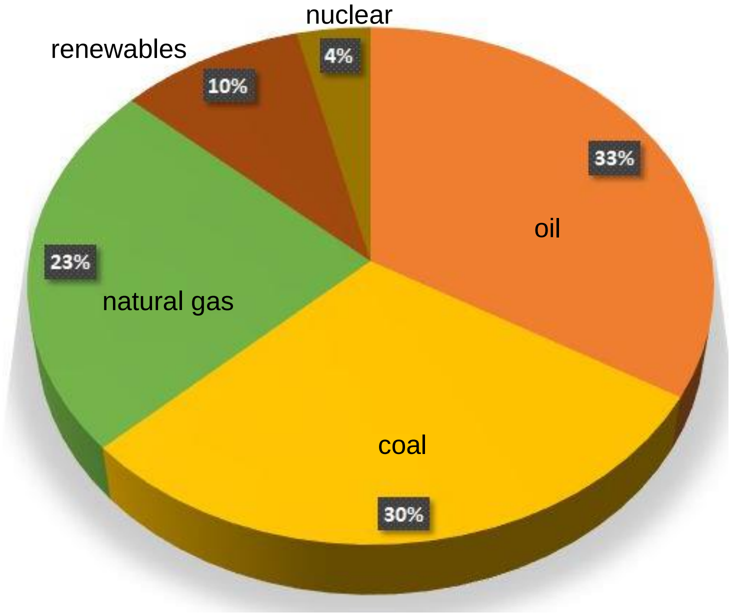


Figure 5.6 is a pie chart plot of recent figures, showing that more than 85% of the world's current power consumption comes from fossil fuels, 10% from renewable sources, and just 4% from nuclear power

Despite attempts across the world to reduce fossil fuel usage and to change to renewable power sources, recent data still show the importance and increasing use of fossil fuel sources. Under current conditions it will clearly take a long time to reverse these trends.

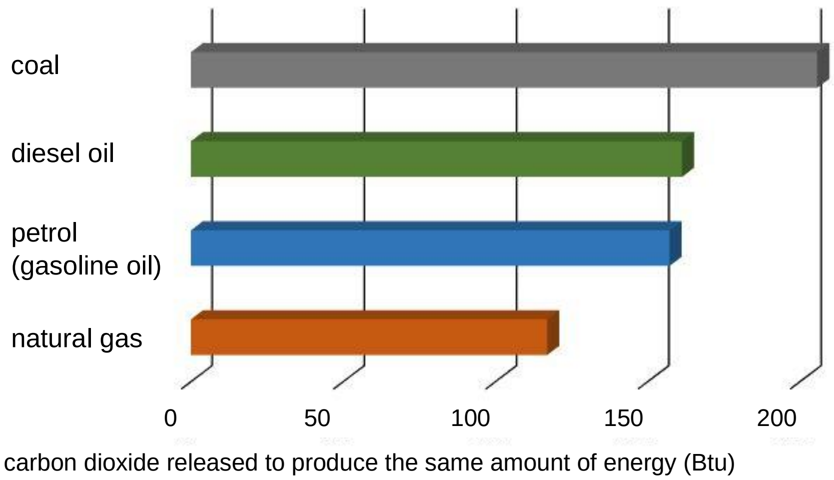
5.2.1 Energy from fossil fuels

Most electricity-producing power stations burn the fossil fuels coal, oil or natural gas. All three are also used to produce chemicals and other industrial products, including plastics.

Oil, once refined, is the most important power source for road and rail vehicles, and the only fuel used in commercial air and sea transportation.

There is global pressure to reduce the use of fossil fuels and to replace them with renewable energy because of the influence of fossil fuel-burning on climate change. The links between carbon dioxide, the greenhouse effect and climate change were explained in Section 4.3.3.

Figure 5.7. The amounts of carbon dioxide released by the burning of different fossil fuels to produce the same amount of energy



The graph in Figure 5.7 shows that the fuel which produces most carbon dioxide when burnt is coal. Coal-burning also releases more pollutants than other fossil fuels. These include sulfur dioxide and nitric oxide gases as well as smoke particles and ash. Globally there are moves to close down coal-fired power stations and replace them with natural gas-fired power stations, because burning natural gas releases only just over half the amount of carbon dioxide that coal does, and greatly reduced amounts of other pollutants too.

Fossil fuels are not renewable. This means that although the conditions for the building up of organic material and conversion into fossil fuels over time do exist today, this is happening very much more slowly than fossil fuels are being extracted. Therefore, there will come a time when most of the fossil fuels on Earth have been extracted – meaning that further extraction will become much more difficult and expensive.

It is because fossil fuels are not renewable and are also polluting that there is a global move towards renewable energy resources.

Box 5.11E. Morecambe Bay – Britain's second-largest natural gas field

Morecambe Bay in North West England lies in the East Irish Sea and is part of an estuary. In 1974, the second largest natural gas field in Britain was discovered in Morecambe Bay about 40 km west of Blackpool. The first gas from this gas field, the South Morecambe Field, came ashore in 1985. At peak production Morecambe provided 15% of the UK's gas supply.

The Central Processing Platform, a three-platform, bridge-linked complex with a flare boom tower

The most likely source rocks of the methane found in the Morecambe Bay gas fields are early Carboniferous organic-rich mudstones and oil shales and late Carboniferous coals. The natural gas is found in porous, permeable sandstone layers within the Triassic Sherwood Sandstone Group. This reservoir rock is capped, or sealed, by impermeable shale and salt (halite) of the Triassic rocks above.

Drilling platforms in the South Morecambe Field are in water depths of 20 metres and the top of the gas reservoir is at a minimum depth of about 700 metres. The reservoir is very large and shallow so that directional, or slant, drilling was used. Using a drilling rig slanted at 30^{o} degrees increases the drilling section length through the reservoir. This meant that only three drilling platforms were needed in the South Morecambe Field as opposed to the seven required if vertical drilling rigs had been used.

Offshore gas platform,
in the South Morecambe Bay gas field

When the South Morecambe Field came online in 1985 the predicted lifespan was 25 years. With recent maintenance, shutting down two of the field's unmanned drilling platforms and refurbishment of other platforms, gas production from the field has been extended into the 2020s.

Maggie Williams

5.2.2 Renewable energy

Sources of **renewable energy** are replaced at least as fast as they are used, and so will continue to be available into the future. They also do not release pollutants during use although they can have other environmental effects. For these reasons, there is global growth in developing and growing renewable energy sources. Figure 5.8 shows that the most widely used renewable energy source today is hydroelectric, followed by solar power, biopower and wind power (Table 5.9). Geothermal and tidal sources generate only small amounts of power globally, whilst wave power remains at the experimental stage.

Figure 5.8. Recent energy production from different renewable sources; data from REN21 global status report, Table R1

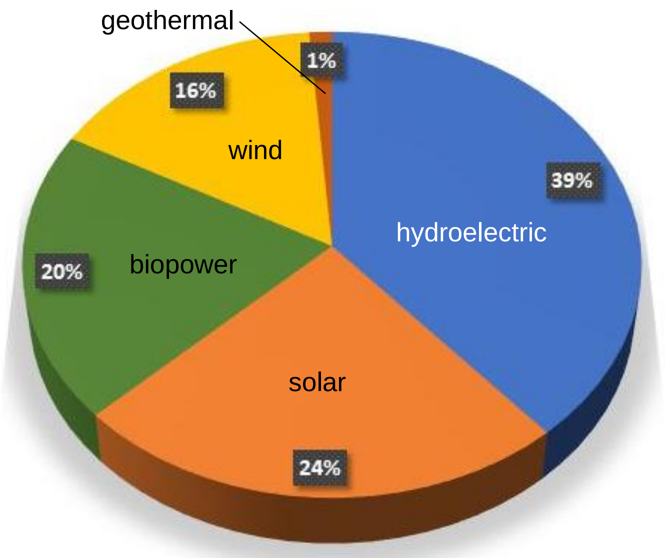


Table 5.9. Renewable energy sources, from the source producing most global energy at the top of the table, to the least at the bottom

Renewable energy source	Detail	Image	Source
Hydroelectric	Hydroelectricity is generated by constructing dams to create reservoirs and channelling water into turbines to produce electricity as it flows out of the reservoir		An Archimedes screw installed recently to generate hydroelectric power at Cragside, Northumberland. Cragside was the first building in the world to have hydroelectric lighting
Solar	Arrays of solar panels are angled to collect the most solar power from the Sun		A solar farm near Bentham in North Yorkshire
Biopower	Most biopower is generated by the burning of biomass (specially grown crops or waste material) to produce electricity, but some crops are used to produce biofuels for transport		Blackburn Meadows biomass power station near Rotherham, South Yorkshire

Table 5.9. Renewable energy sources, from the source producing most global energy at the top of the table, to the least at the bottom, continued

Renewable energy source	Detail	Image	Source
Wind	Wind farms are built of groups of wind turbines, either on land or offshore		The Burbo Bank offshore wind farm on the Burbo Flats in Liverpool Bay, in the Irish Sea
Geothermal	Geothermal power is generated in volcanic regions, where it is usually called hydrothermal power; it is also extracted from warm rocks in other areas		The Southampton geothermal plant, using warm water from a deeply-buried Triassic aquifer – used to heat buildings in a 4km wide circle around the plant
Tidal	Tidal power is being generated on a small scale in several countries but, so far, there are no large-scale commercial tidal power plants		Neptune, an experimental tidal power plant installed in the estuary of the river Humber to generate electricity for the Hull aquarium in East Yorkshire
Wave	Wave power is not yet being used commercially on a large scale, but small-scale generators are being tested		One of the three Pelamis machines bursting through a wave at the Aguçadoura Wave Park, Portugal

Box 5.12E. Offshore wind power

The UK is at the cutting edge of wind energy technology, helped by regular winds and large areas of coastal waters. It is currently the world leader in offshore wind and has been generating more than 20% of its electricity from wind power in recent years.

There are plans to greatly increase offshore wind power in future, particularly in the Irish Sea off Cumbria and the North Sea off Yorkshire.

Rampion offshore wind farm, off the coast of East Sussex. Photo taken from a plane

Kentish Flats wind farm, off the north Kent coast

Thanet offshore wind farm, Kent

Chris King

Two of the problems with some sources of renewable energy are that their output is variable, and we currently have no method for storing their power on a large scale. So, on days when there is little sunshine (solar), winds are light or too strong (wind power), tidal currents are reduced (during neap tides) or waves are small (wave power), some other source of power is needed to provide a regular ‘base load’ supply. Large-scale base load supply has traditionally been provided by fossil fuels and nuclear sources which can be switched on and off fairly easily according to need.

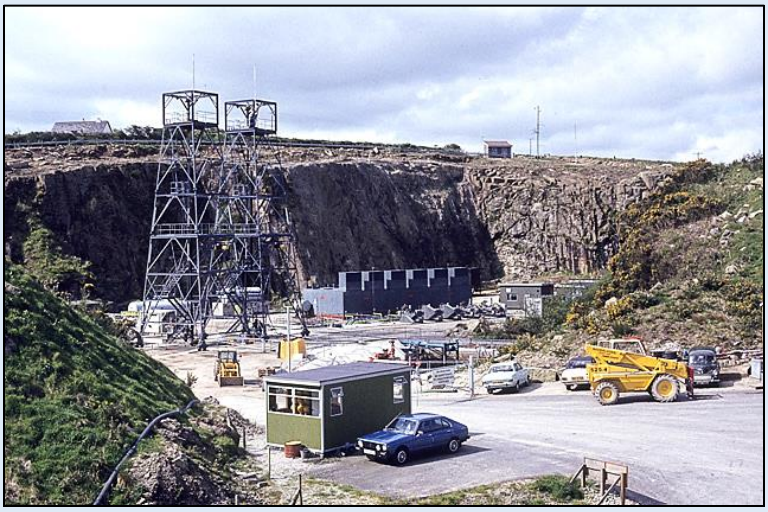
Whilst renewable power sources are renewable and generate no pollution during use, they all have environmental impact, because they use raw materials and energy during construction. Some are criticised for other reasons as well: generating hydroelectric power requires large dams to be built and valleys to be flooded by reservoirs; solar panels use expensive rare earth elements in their construction; biocrops may be grown on land useful for other types of agriculture; and wind turbines are expensive to build; some people think that views of wind turbines improve the environment, and others the opposite.

Box 5.5. Geothermal energy – is it renewable?

Geothermal energy can be obtained from three different geological situations:

- Where igneous rocks in large plutons have become warm due to the decay of the radioactive minerals they contain: two boreholes are drilled and the rock between them is fractured; water is pumped down one borehole, warms as it flows through the fractures and is extracted from the second hole; heat is taken from the warm water and it is recycled by being pumped back down again. This is hot dry rock geothermal energy.
- Where there are deeply buried aquifers of groundwater: heat from deep in the Earth has warmed the water, and it has stayed warm because of the thick insulating layers of sediment above. This warm water is pumped out and recycled, in the same way as described above. This is hot wet rock geothermal power
- In areas of volcanic activity: waters heated by magma chambers below become hot and may rise from below in hot pools and geysers; these hot waters can be extracted by boreholes and used to drive turbines in hydrothermal power stations. This is hydrothermal energy.

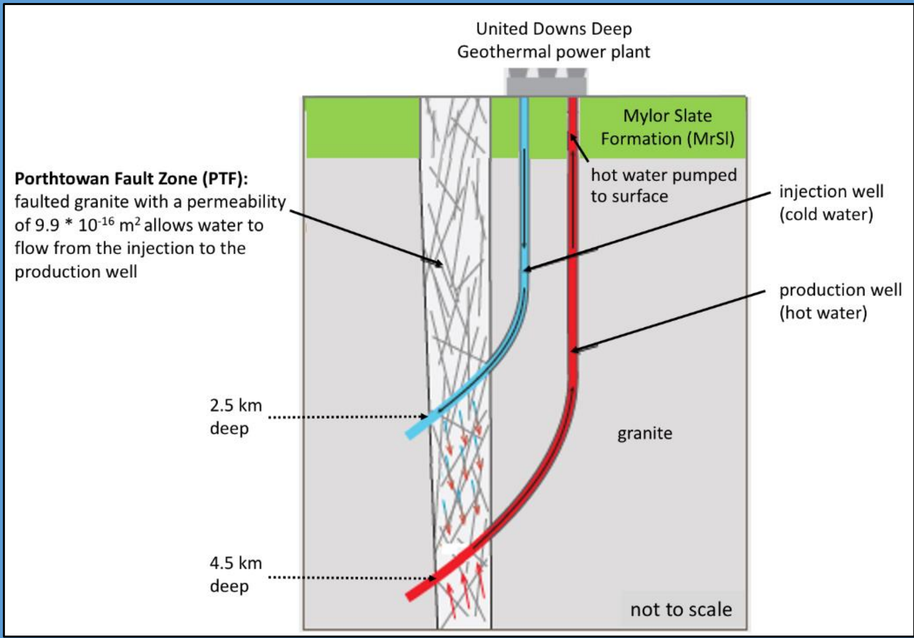
In both hot dry and hot wet rocks, the heat has built up in the rocks over many thousands of years and is extracted much faster than it can be replaced, so these types of geothermal power are not renewable. Where there are hydrothermal power stations, the heat is usually extracted at faster rates than it is being renewed. Such power stations must eventually close and new ones opened elsewhere in the hydrothermal field; so this energy is not usually extracted renewably either.



Experimental hot dry rock geothermal energy plant at Rosemanowas, Cornwall in 1983

Note: energy taken from the ground by local ground source heat pumps is also sometimes called geothermal energy; however, most of the energy extracted in this way comes from warming of the land surface by the Sun and not from underground heat sources. This is a renewable resource, even though it does need some electricity to operate the system.

Box 5.13E. Geothermal energy in Cornwall



The United Downs Deep Geothermal Power Project (UDDGP) will be the first geothermal power plant in the UK. The project will produce power from the hot Carnmenellis Granite beneath Cornwall, at the United Downs Industrial Site, near Redruth in Cornwall. Water, pumped down an injection well travels through fractures in the rock, becoming heated up as it does so, until it is pumped out of a production well as hot pressurised water. This will then be converted into electricity by a steam turbine.

Two wells have successfully been drilled; a production well to a depth of 4500 m and the injection well to 2393m. Both wells have cut the Porthtowan Fault Zone, where the fractures in the zone increase the permeability of the granite. The fracturing allows water to circulate between the wells at a rate fast enough for the project to be successful.

Temperature rises at a rate in the granite of 0.04°Cm^{-1}, so that the temperatures at the end of the wells should be ~190°C. This will give a predicted water temperature of ~175°C when it reaches the surface, which should produce up to 10MW of electricity. The water will then be reinjected at a temperature of approximately 80°C to complete the water flow system. If this is successful the power plant will begin commercial operation in 2021.

Pete Loader

Box 5.14E. A site for the deep geological disposal of high-level radioactive waste – Sellafield?

In 1982 the UK government set up the Nuclear Industry Radioactive Waste Executive (NIREX) to explore the options in the UK for disposing of high-level radioactive waste, mostly generated by nuclear power stations. The search eventually focussed on a deep geological repository, which would normally be from 200-1000m below the surface. The two most important geological requirements were stability, where earthquakes were not likely to cause problems, and very slow water movement in low permeability rocks. NIREX eventually developed five possible options:

- hard rocks in lowland areas – where there would be little groundwater flow;
- seaward-dipping sedimentary rocks – where any low groundwater flow would be into the sea;
- low permeability deep rocks under sedimentary rocks – low permeability having little flow;
- inland sedimentary rocks in a basin or syncline – where flow would be trapped in the centre;
- small islands of different rock types – where any leakage would be into the sea.

Box 5.14E. A site for the deep geological disposal of high-level radioactive waste – Sellafield?, continued

Eventually NIREX decided that the best place to investigate further was the area near the Sellafield Nuclear Power station in Cumbria. This was because there were low permeability deep rocks under sedimentary rocks there, and also because, as most of the UK high-level radioactive waste was already in near-surface storage there, it would not be necessary to transport the waste, with the linked safety issues, if the deep repository was nearby.

Sellafield nuclear power station, Cumbria

After further geological exploration, NIREX applied to the government to construct an underground laboratory to further investigate the rocks. At the following public inquiry, permission was refused, and NIREX appealed. The Secretary of State turned down the appeal in 1997, after which NIREX was closed down. The disposal of high level radioactive waste issue is currently being reviewed by the 'Radioactive Waste Management' government organisation.

Chris King

6 Human/Earth's system interactions

Without Earth system interactions, life on Earth in general, and human life in particular, could not exist. So, whilst many of the interactions below have negative or even devastating effects, we must not forget that without the combination of atmosphere and ocean, rocks and soils, highlands and lowlands, and the other features of Earth systems, life as we know it would not be possible.

6.1 Natural hazards

Natural processes become **hazards** only when human life and property are at risk; if there is a landslide in a remote region, it is just a landslide, not a hazard. The best way to deal with a natural hazard is for the planning authorities to ensure that people do not live in hazardous areas. Where this is not possible, other means are taken to reduce or **mitigate** the risk.

6.1.1 Eruption

When rising magma reaches the Earth's surface it erupts; some eruptions are fairly safe and spectacular, but others are catastrophically dangerous. The range of different sorts of volcanic activity depends mainly on the runniness (viscosity) of the magma. When magma reaches the surface and erupts, it is no longer called magma: it either flows out of volcanoes as lava, or is blasted out as fine ash, larger solid blocks or liquid lava 'bombs' (Figure 6.1.).

Figure 6.1. 'Bombs' of liquid lava erupted at night by the Stromboli volcano, near Sicily, Italy, 2013

The viscosity of magma depends on its chemical composition, its temperature and how much volcanic gas and crystals it contains. Sections 4.1.2.3. (Igneous processes) and 4.1.4. (Plate tectonics) show that different plate margins generally have magmas with different compositions.

The most common magmas at constructive plate margins are the iron/magnesium-rich magmas that produce basalts. At subduction zones the less iron-rich (intermediate) magmas that produce andesite lavas are most commonly erupted, although silicon-rich magmas sometimes erupt there too. The balance between iron/magnesium and silicon composition changes the runniness: iron/magnesium-rich basaltic magmas are the most runny (low viscosity) at one end of the scale and silicon-rich are the least runny (highly viscous) at the other end. Basaltic magmas are also usually the hottest, and the hotter the magma is, the less viscous it is as well. Basaltic magmas also tend to contain few crystals, increasing their runniness. When magmas contain a lot of gas this makes them more runny too, although basaltic magmas usually do not contain much gas. So in summary, iron/magnesium-rich basaltic magmas are free-flowing with low viscosity, while intermediate and silicon-rich magmas are very sticky with high viscosity.

When runny basaltic magma erupts as lava, it pours out of the ground along long surface cracks or through volcanic vents and may be sprayed into the air as spectacular lava fountains. Rivers of lava can flow over the ground or move more slowly as blocky masses bulldozing along. These are spectacular eruptions that are usually quite safe if you do not get too close.

The eruption of intermediate and silicon-rich magma is very different. It erupts from vents, sometimes as lava, but usually the magma becomes solid within the volcanic vent, giving much more explosive eruptions, as shown in Table 6.1.

Table 6.1. Volcanic processes and their effects

Volcanic process	Description		Image	Source
Lava eruption	Usually low viscosity	Lava can spray out of fractures as lava fountains, before flowing as rivers of lava down the slopes of the volcano; these quick-flowing lavas result in shallow-sided volcanoes or, if under water, in pillow lavas		Lava fountains and lava flow, Hawaii, 2004
Lateral blast	Usually high viscosity; magma solidifies in vent leading to explosive eruption	When an eruption erupts sideways instead of upwards, it can produce a lateral blast that devastates hundreds of square kilometres of country in the blast direction		Large trees flattened by the Mount St Helens blast, 1980 (human figures for scale, bottom right)
Ash/block eruption		Volcanic ash plumes are erupted high into the atmosphere. Solid blocks are also expelled and rain down producing a steep-sided volcanic cone. Ash can be carried by wind far away		Mount St Helens ash eruption, Washington State, USA, 1980
Nuée ardente/ pyroclastic flow		Erupted volcanic ash clouds can flow at high speed down the sides of volcanoes as high-temperature density currents called nuées ardentes (glowing clouds) or pyroclastic flows		Nuées ardentes flowing down Mayon Volcano in the Philippines, 1984

Table 6.1. Volcanic processes and their effects, continued

Volcanic process	Description		Image	Source
Lahar flow	Usually high viscosity; magma solidifies in vent leading to explosive eruption	When volcanic ash is picked up by water from a crater lake, melted ice/snow on a volcanic peak or an eruption-related thunderstorm, it flows downhill like high-speed concrete, sometimes for many kilometres		Lahar burying houses near Galanggung volcano, Indonesia, 1983

The Volcanic Explosivity Index measures the explosiveness of volcanic eruptions, ranging from non-explosive to mega-colossal, as shown in Table 6.2.

Table 6.2. Eruptions according to the Volcanic Explosivity Index (VEI), showing plume height (m), volume of material ejected (m^3) and approximately how often that type of eruption occurs (global frequency)

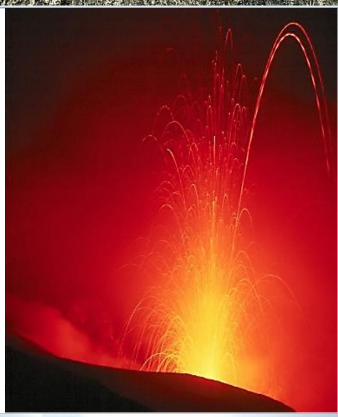
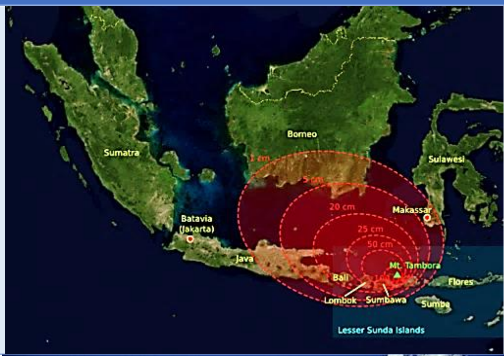
VEI	Description	Plume height Volume Global frequency	Image	Source
0		< 100m high 1000s m^3 volume continuous		Glowing lava flowing from the Pu‘u ‘Ō‘ō volcanic cone, Kilauea, Hawaii, 1997
1	gentle	100-1000m high 10,000s m^3 volume daily		Eruption of Stromboli at night; volcanic bombs being fired more than 100m into the air, Italy, 1980
2	explosive	1-5 km high 1,000,000s m^3 volume weekly		Eruption of Mount Sinabung, Medan, Indonesia, which killed the vines in the foreground, 2014

Table 6.2. Eruptions according to the Volcanic Explosivity Index (VEI), showing plume height (m), volume of material ejected (m^3) and approximately how often that type of eruption occurs (global frequency), continued

VEI	Description	Plume height Volume Global frequency	Image	Source
3	severe	3-15 km high		Nevado del Ruiz; this lahar of erupted ash buried the town of Armero in the centre, Columbia, 1985
		0.01 km^3 volume		
		monthly		
4	cataclysmic	10-25 km high		Eruption plume of the Calbuco Volcano near Puerto Varas, Chile, 2015
		0.1 km^3 volume		
		2 years		
5	paroxysmal	> 25 km high		Satellite view of the 800 km-long ash plume from the 2011 Puyehue-Cordón eruption, Chile
		1 km^3 volume		
		10 years		
6	colossal	> 25 km high		Ash plume of Pinatubo during the 1991 eruption in the Philippines
		10s km^3 volume		
		50 – 100 years		

Table 6.2. Eruptions according to the Volcanic Explosivity Index (VEI), showing plume height (m), volume of material ejected (m^3) and approximately how often that type of eruption occurs (global frequency), continued

VEI	Description	Plume height Volume Global frequency	Image	Source
7	super-colossal	> 25 km high 100s km^3 volume 500 – 1000 years		Estimated area covered by ash fall from the Tambora eruption, Indonesia, 1815
8	mega-colossal	> 25 km high 1,000s km^3 volume > 50,000 years		The huge volcanic crater (caldera) from three Yellowstone eruptions, Wyoming, USA – latest 630,000 years ago

It can be difficult to picture what large eruptions might actually mean for the people living nearby, or to understand how they can affect the whole Earth, but case studies of particular eruptions give some idea.

Box 6.1. A colossal eruption – Krakatoa, 1883

The VEI 6 eruption of Krakatoa in Indonesia was the first colossal eruption to be reported globally, thanks to the new global telegraph links of the time and widespread reporting in newspapers, like *The Times* in London.

VOLCANIC ERUPTIONS IN JAVA

BATAVIA, Aug 27

Terrific detonations from the volcanic island of Krakatoa were heard last night, and were audible as far as Soerakarta, showers of ashes falling as far as Cheribon. The flashes from the volcano are plainly visible from here. Serang is now in total darkness. Stones have fallen at that place. Batavia is also nearly in darkness. All the gaslights were extinguished during the night. It is impossible to communicate with Anjer and it is feared that some calamity has happened there. Several bridges between Anjer and Serang have been destroyed and a village near the former place has been washed away, the rivers having overflowed through the rush of the sea inland.

The Times reporting on the following day shows how the scale of the tragedy began to unfold, as news from different sources began to filter in.

Artist's impression drawn soon after the eruption

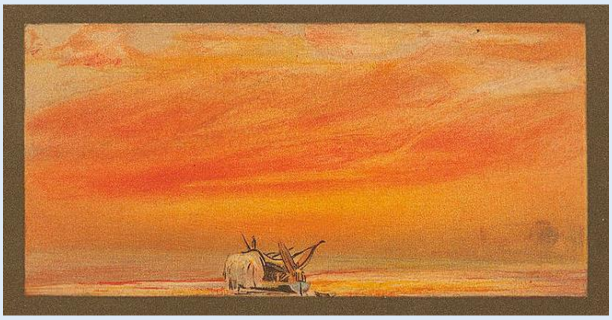
Box 6.1. A colossal eruption – Krakatoa, 1883, continued

The full scale of the disaster only became clearer later, when many more stories of the eruption were collected locally, geologists examined the area, and observations from scientists around the world were collected.

The investigation showed that:

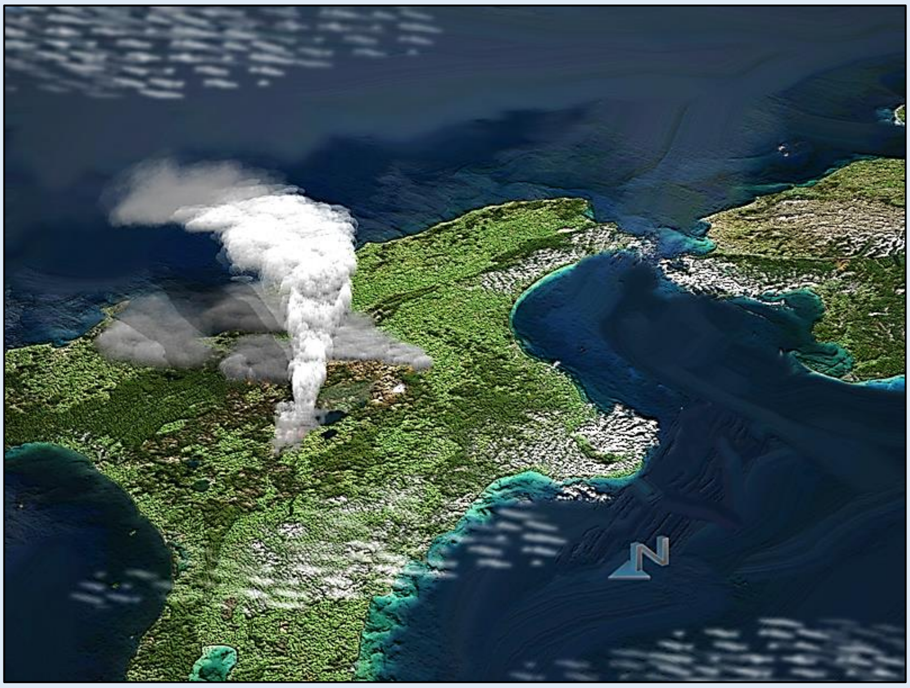
- nearly three-quarters of the small island of Krakatoa had been destroyed in the final eruption
- nearly 40,000 people were killed by the eruption and the tsunamis it produced
- an ash cloud was seen rising 27 km into the air
- 10cm-wide pieces of pumice fell onto the decks of ships more than 20km away
- huge islands of floating pumice floated across the ocean for months
- about 20km^3 of material was erupted
- people heard the explosion up to 4,800 km away, on Rodrigues Island in the Indian Ocean (where the governor thought there must be a sea battle offshore) and in the Australian towns of Perth and Alice Springs
- this explosion was the loudest sound heard on Earth in the past two centuries;
- the resulting tsunamis were more than 30m high
- small tsunami waves were recorded in the English Channel, on the other side of the globe
- the atmospheric shock wave was recorded all over the world, circling the globe several times
- ash rose 80 km high in the atmosphere and affected global weather patterns for years afterwards
- ash was carried through the upper atmosphere by the jet stream, the first time this had been seen
- in the following year, global temperatures in the Northern Hemisphere fell by an estimated 1.2ºC as sunlight was reflected back into space by the high-level clouds produced by the volcanic gases released;
- the ash produced spectacular sunsets around the world for several months and the Sun and Moon sometimes appeared in odd colours
- the energy released by the eruption is thought to have been about four times the power of the largest nuclear bomb ever exploded.

These observations give a good idea of what a 'colossal' eruption is actually like.




Paintings of the sky in the 'afterglow' caused by the ash of the Krakatoan eruption in 1883, by William Ashcroft

Box 6.2. A mega-colossal eruption – Oruanui eruption, around 25,360 years ago



Artist's impression of the Oruanui eruption from space

The Oruanui mega-colossal eruption of the Taupo volcano is the most recent VEI 8 eruption to affect the Earth. The eruption was some 25,000 years ago, long before humans colonised New Zealand. This is just as well, because the eruption probably devastated the whole of New Zealand. Since we have no eye-witness stories of the eruption, we have to base our ideas of what the eruption was like on the geological evidence. This shows:

- 1170km^3 of silicon-rich material was ejected, nearly 60 times the amount of material erupted by Krakatoa in 1883
- 430km^3 of ash was erupted into the sky, falling over most of New Zealand as thick ash deposits; 18cm thicknesses of ash were recorded on islands 1000km away
- 320km^3 of ash was erupted sideways in nuées ardentes, leaving deposits up to 200m thick
- the magma chamber collapsed forming a huge crater (caldera) more than 30 km across, now filled by Lake Taupo
- the course of the Waikato river was moved so that it now reaches the sea on the west coast of North Island, instead of the north coast.

This is how the New Zealand area was affected, but there are no records of the impacts on the rest of the Earth because the eruption happened long before writing was invented. Being in the centre of North Island, the eruption may not have produced tsunamis, but the eruption of huge amounts of ash and volcanic gas into the atmosphere must have had worldwide climatic effects. If the VEI 7 eruption of Tambora in Indonesia in 1815 could produce a 'Year without summer' and famine in Europe, the global effects of the VEI 8 Oruanui eruption can only be imagined, since it erupted maybe ten times the amount of ash and volcanic gas into the atmosphere.

Eruptions of high explosivity volcanoes can be so devastating that scientists have been working for many years to predict them. A wide range of different volcano monitoring methods has been tested; some of these are described in Table 6.3. The problem with all these methods is that they can show that an eruption is likely, leading to the evacuation of the surrounding areas, only for the signs to die away again, without any eruption. After this people are less likely to obey the next evacuation order. So, while we know that eruptions of currently active volcanoes will occur, predicting the exact time and scale of eruptions remains a very difficult task.

Table 6.3. Methods used to monitor volcanic eruptions

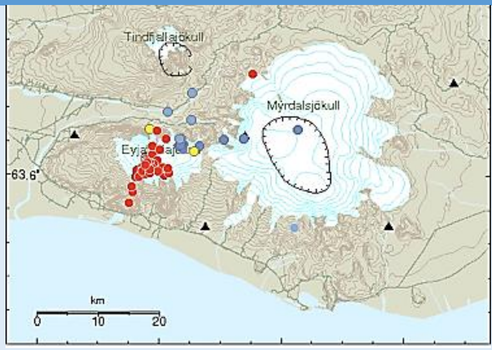
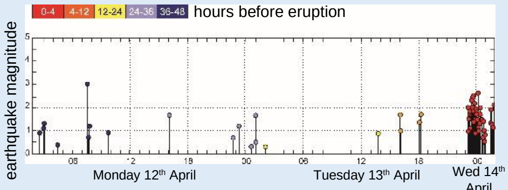
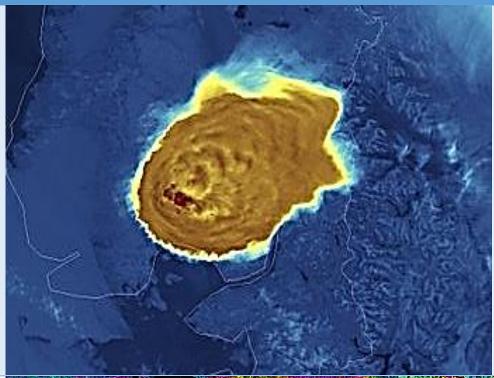
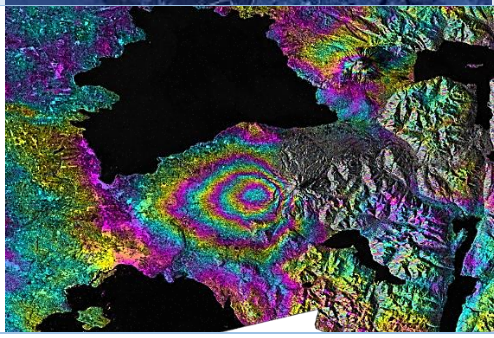
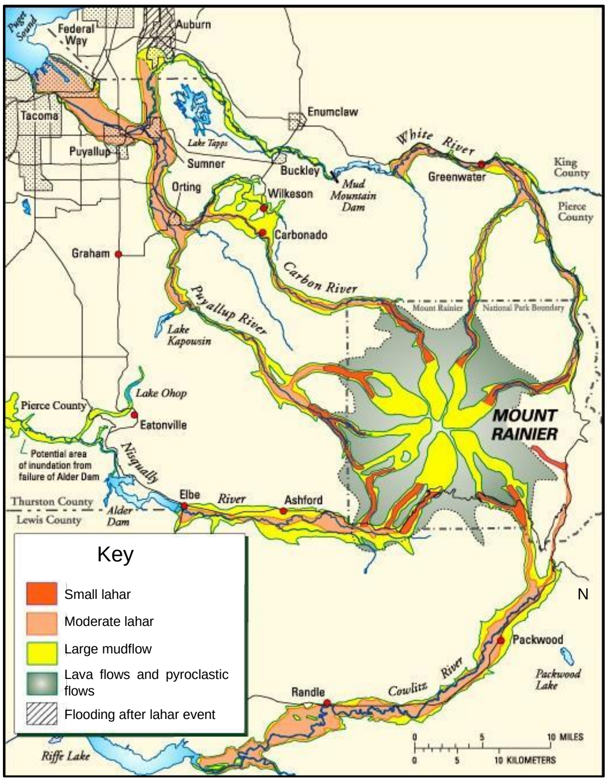
Eruption monitoring method	Description	Image	Source
Seismicity	Different sorts of earth tremors can be produced in the build-up to volcanic eruptions, including the harmonic tremors thought to be produced by flowing magma underground	  Timing and size of earthquake tremors before the eruption of Eyjafjallajökull at 01.55 on Wednesday 14th April 2010	Earthquakes linked to the 2010 eruption of Eyjafjallajö-kull in Iceland
Gas emissions	Venting of gas can increase or decrease before volcanic eruptions, giving clues to future eruptions		Yellow sulfur in a volcanic gas vent; gas being monitored by a sensor, White Island, New Zealand
Ground deformation	Swelling of a volcano shows that magma is building up near the surface. This can be monitored by measuring how the position of a station changes, using the Global Positioning System (GPS), and also by measuring changes in slope, using tiltmeters, and in strain, using strain gauges		GPS monitoring station, Piton de la Fournaise volcano, Réunion Island, Indian Ocean

Table 6.3. Methods used to monitor volcanic eruptions, continued

Eruption monitoring method	Description	Image	Source
Thermal monitoring	Magma movement, gas release and hydrothermal activity can heat up a volcano before an eruption; this can be detected by satellites and on the ground. Ground measurements can measure the surface temperature directly, or monitor changes in hot springs or water wells		Thermal image; high heat flow (red, brown and yellow) in the crater of Calbuco in Chile, 2015, against the cool blue background of the land
Remote sensing	Satellites can monitor temperature, as above, and also deformation of the ground, as well as the release of volcanic gases and the eruption of ash clouds produced by volcanoes		Ground deformation shown in a false colour satellite image, linked to the 2015 eruption of Calbuco, Chile

The most effective way to mitigate or reduce risk from volcanic eruptions is for land-use planning to stop people from building in hazardous areas. Hazardous areas can be investigated by surveying areas geologically for the signs of dangerous eruptions in the past, and then producing hazard maps (for example, Figure 6.2).

Figure 6.2. An example of a volcanic hazard map, Mount Rainier, Washington State, USA, predicting what might happen in a major volcanic eruption



Where it is not possible to build outside hazardous areas, then steps are taken to prepare for damaging eruptions. These include monitoring volcanoes and preparing for emergency responses to alerts. The population is trained what to do in an emergency, and systems are set up to warn the population. The emergency services are trained to evacuate people and in search and rescue methods. Preparations are made to help people to deal with the catastrophe of losing homes and property, and to rebuild settlements either in the same place or elsewhere.

Where systems like these have been set up they have been successful. Mitigation of the 1991 VEI 6 colossal eruption of Pinatubo in the Philippines saved 5000 lives and 250 million US dollars-worth of property. Mitigation of the 1995 VEI 3 catastrophic eruption on the island of Montserrat in the West Indies saved 11,000 lives.

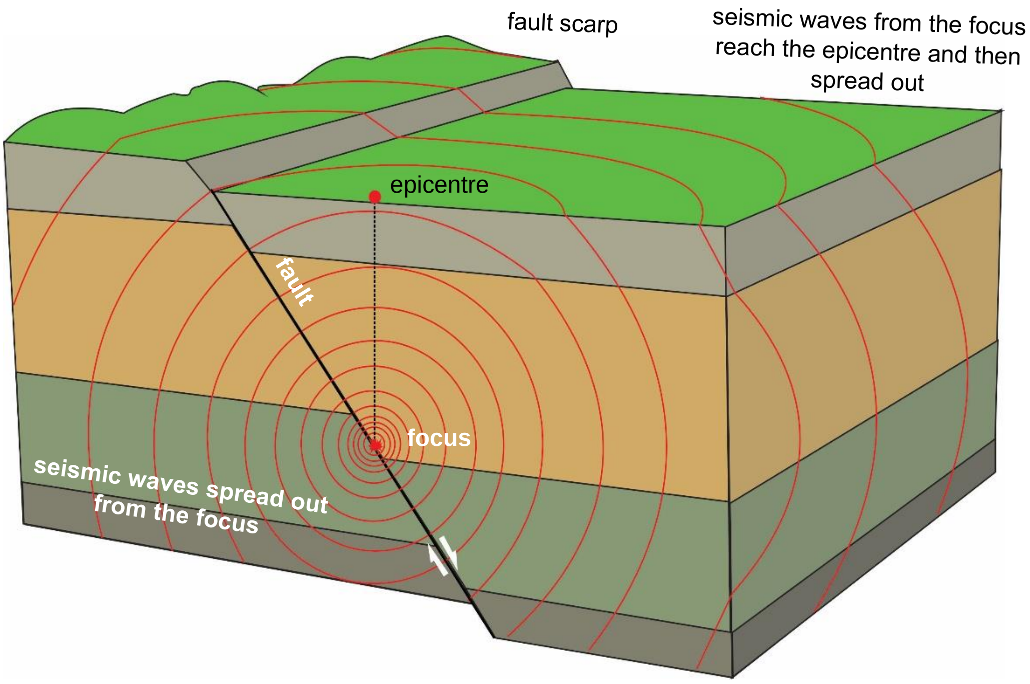
6.1.2 Earthquake

Major earthquakes are caused by faulting, but this did not become clear until the studies by H.F. Reid in 1911. Before then, people had little idea of what caused earthquakes, so it is not surprising that many myths and stories grew up around the world to explain these catastrophic events.

Pressures in the Earth build up until the rocks underground break or fracture along a fault, when both sides move past each other. The fracture point, where there is most movement, is the **focus** (or hypocentre). The sudden break produces shock waves that radiate out in all directions as earthquake waves. Shock waves that travel through the Earth are called **seismic waves**.

Where the shock waves reach the Earth's surface, directly above the focus, is where the earthquake is strongest, and where there is most damage; this is the **epicentre** (Figure 6.3). The shock waves radiate out across the Earth's surface from the epicentre, like ripples on a pond, reducing in power as they do so. Normally most earthquake damage happens at the epicentre, although other factors, like the strength of the ground and of foundations, can cause more damage in some places than others.

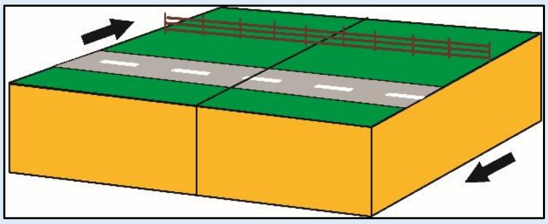
Figure 6.3. An earthquake producing seismic waves



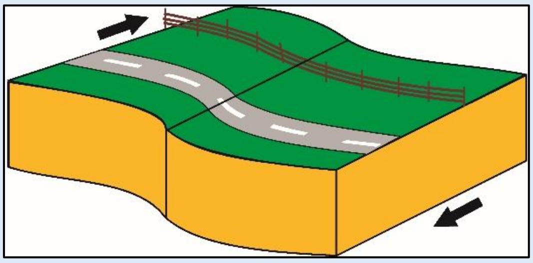
Box 6.3. The elastic rebound theory

A scientific theory to explain earthquakes was developed in 1911 by H.F. Reid, by studying parts of the San Andreas fault in California, USA. He plotted the movement of points on either side of the fault and realised that the land was moving in different directions on either side of a fault before the earthquake. As the pressure built up, the land on either side bent. Finally, it couldn't bend any further and the fault broke, sending out shock waves in an earthquake. He called this his 'Elastic rebound theory' because the ground bounced back elastically when the fault moved.

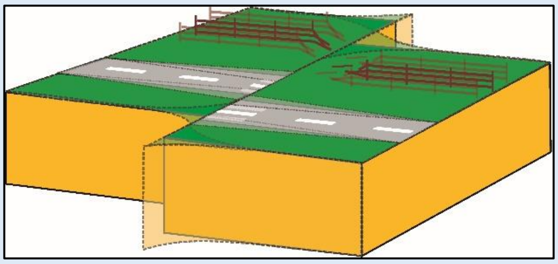
1. Fence and road are built over locked fault



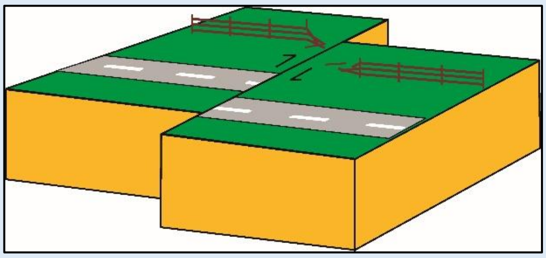
2. Pressure builds up, the rock, fence and road bend



3. The fault suddenly breaks, the rock rebounds elastically (bo-ing!) causing an earthquake



4. After the earthquake, the fault has moved, the fence and road are straight again, but are broken across the fault



Movement of the ground in H.F. Reid's 'Elastic rebound theory'

Small earthquakes, usually called earth tremors, are so small that they can only be detected by seismic detecting devices called **seismometers**. Seismometers are so sensitive that they can detect the vibrations from heavy trucks or trains, quarry blasts and even the shout of the crowd when a goal is scored in a football stadium. Networks of seismometers have been sited across the globe and not only show the size of earthquake, but also the location of its epicentre and depth to its focus. This work was used to map the locations and depths of earthquakes in Table 4.22, used as evidence for plate tectonic theory.

Box 6.4. Seismometers

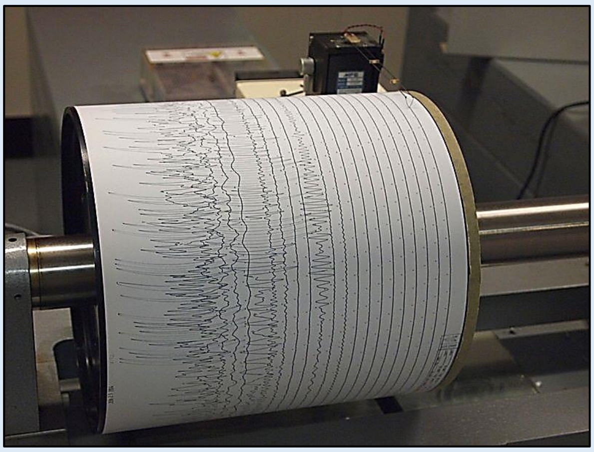
Seismometers have a mass suspended inside, such that when the Earth moves the seismometer, the mass inside moves more slowly. The difference between the movement of the seismometer and the mass inside is magnified and is recorded by a pen on a drum that rotates over time, or as an electronic record. Outdoor seismometers are usually sited in holes in the ground with the recording equipment nearby, including equipment to send the data to a recording laboratory. Seismometers indoors must be mounted on concrete ground floors; the upper floors of buildings vibrate too much. Modern mobile phones have a similar vibration sensor, which can be used as a seismometer by downloading the correct app.

Box 6.4. Seismometers, continued

Recording equipment for one of an array of seismometers that is sited in a hole nearby, Gulf of Corinth, Greece

Recording equipment and back-up electricity supply for a Gulf of Corinth seismometer

Two seismometers, older one on the left, more modern one on the right, Patras Seismological Laboratory, Greece



Drum record from a seismometer

Seismometers can measure the power or magnitude of an earthquake at the epicentre. This used to be recorded using the Richter scale, but nowadays the Moment Magnitude scale is used instead. The power of an earthquake at each level is ten times the magnitude of the previous level of earthquake (Table 6.4).

Table 6.4. The Moment Magnitude scale

Moment magnitude	Description	Damage	Approx. number per year
Less than 3	Not felt by people	None	Great number
3 - 5	Minor	Little	150,000
5 - 7	Moderate to strong	From slight to damaging	150
7 - 8	Major	Serious	15
More than 8	A ‘great’ quake	Catastrophic	1

The largest earthquake ever recorded so far was the 9.5 magnitude earthquake in Chile in 1960. A magnitude 10 earthquake has never been recorded.

Details of some major earthquakes, recorded in order of the approximate number of deaths, are shown in Table 6.5.

Table 6.5. Some of the most dangerous earthquakes, according to the numbers of deaths

Earthquake	Date	Location	Deaths	Magnitude	Comment
Haiyuan	16 December, 1920	Ning-Gansu, China	More than 270,000	7.8	Shaking, ground fracture and landslides
Tangshan	28 July, 1976	Hebei, China	More than 240,000	7.8	Shaking magnified by soft ground
Indian Ocean	26 December, 2004	Off Sumatra, Indonesia	More than 230,000	9.2	Most deaths caused by tsunami
Haiti	12 January, 2010	Haiti, Caribbean Sea	100,000 – 316,000	7.0	Shallow depth of focus caused strong shaking
Kantō	1 September, 1923	Kantō, Japan	More than 100,000	7.9	Firestorms caused by the earthquake caused many deaths
Kashmir	8 October, 2005	Muzaffarabad, Pakistan	More than 85,000	7.6	Severe shaking
Tōhoku	11 March, 2011	Off Sendai, Japan	More than 15,000	9.0	Most deaths caused by tsunami; nuclear power station damaged

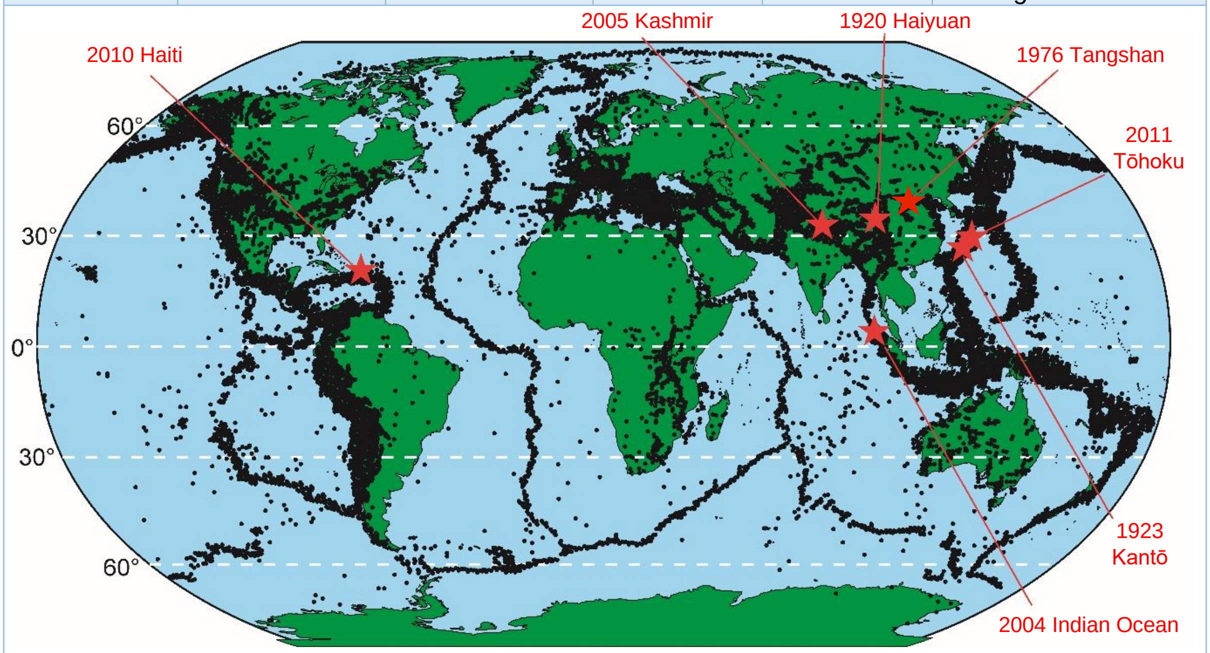


Table 6.5 shows some of the different factors that can make earthquakes so dangerous. In most earthquakes the main cause of death is the shaking of the ground surface causing buildings to collapse. Police Lieutenant H.N. Powell described this during the 1906 earthquake in San Francisco: "*Valencia Street … began to dance and rear and roll in waves like a rough sea. … It was impossible for a man to stand. … Houses were cracking and bending and breaking the same as the street itself.*" Shaking and destruction can be much worse when the ground is soft, as when buildings have been constructed on old lake deposits or on reclaimed ground.

It is worth remembering the old saying, '*It is not earthquakes that kill people, but buildings*'.

Deep faults can sometimes reach the surface as fractures, damaging large structures like bridges, dams and nuclear power stations. Earthquakes trigger landslides and avalanches in areas with steep slopes. Fractured electrical and gas mains cause fires, which cannot be controlled if water mains have also been broken. Some earthquakes cause tsunamis, which can be very damaging in coastal areas. All these factors add to earthquake risk.

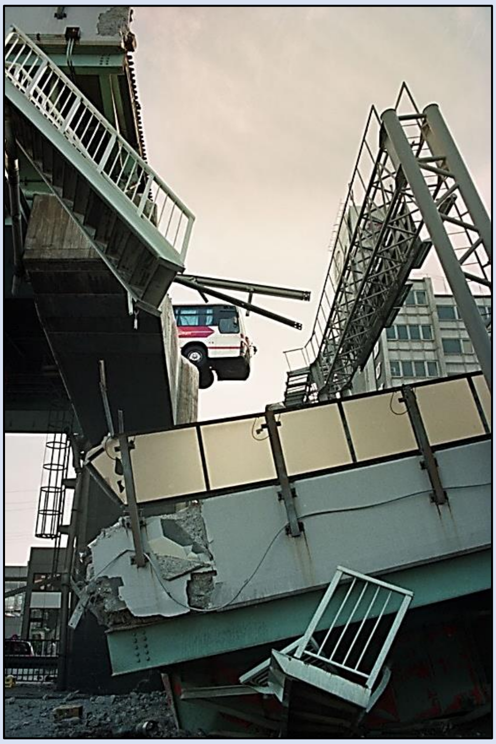
Table 6.5 shows that the number of deaths may not be closely linked to the magnitude of an earthquake. Where earthquakes hit modern towns and cities that have prepared for them, the death toll is usually much lower than earthquakes in less-developed regions. In less-developed areas, buildings may have been poorly constructed, and recovery may be slow due to collapsed communications and poor preparations. For example, the death toll for the 7.0 magnitude earthquake in Haiti in 2010, shown in Table 6.5, was more than 100,000 because most of the buildings were of poorly reinforced concrete. When a much larger 8.8 magnitude earthquake hit Chile in the same year, the death toll was only 520, because earthquake-resistant building codes had been strongly enforced.

Box 6.5. The Kobe earthquake, Japan, 1995 – magnitude 6.9

Akatsukayama High School Student, Yasuyo Morita (17 years old)

'At that time I was sleeping. First I thought my mother was waking me up, but I knew from her scream – it is an earthquake! I didn't know what to do in the dark. The stairs are destroyed, so I went down using a ladder with bare feet wearing pyjamas. I couldn't stop my tears because of darkness and coldness. I was in a panic. There are [a] lot of wooden houses in my neighbourhood. Now they are destroyed without pity. Soon it got lighter and I could see my surroundings. Some went mad. I went to hospital with my grandmother who was rescued from a heap of rubble. Her finger was tearing off. We got to hospital. It was a hell on the earth. A man bleeding from his head, a child – purplish maybe because of suffocation. It was filled with people. My grandmother was disinfected, that's all. Her injury was not serious compared with others. My grandmother's house and my grandfather's house, both are burned down. We couldn't get out anything. The town I like changed in a moment. I was sad. Now I live in one of [the] refuges and I get scared during the night. I want to see Kobe rebuilt again soon.'

From: http://www.sln.org.uk/geography/7-11kobe.htm



The earthquake struck Kobe city in Japan at 05.46 in the morning of 17 January, 1995 when most people were still asleep. The earthquake measured 6.9 on the Moment Magnitude scale; its focus was on an active fault line at a depth of 17 km. In some areas there were up to three minutes of violent shaking. Movement on the fault was triggered by the subduction of the Philippine Sea plate under the Eurasian plate, which carries Japan.

The epicentre was 20km away from the city of Kobe, with its population of 1.5 million people. Around 4,600 of the Kobe population lost their lives, mainly killed by collapsing buildings. Many fires raged over the city, caused by broken gas and electricity lines. Softer ground in the port area liquefied, so that buildings toppled over and cranes fell into the sea. Many transport links were destroyed and a raised motorway through the city collapsed. Electrical cables, gas, water and sewerage pipes were all broken, adding to the problems. The rescue services couldn't easily reach the city and, once there, were faced with blocked roads and broken communications. The high-speed bullet train track and two other railways were broken, cutting communications in Japan in half.

Most of the buildings that collapsed had been built according to 1960 building codes; buildings constructed to more recent building codes mostly survived. Following the earthquake, many volunteers travelled to the area to offer help, the country's disaster prevention plans were improved and were much more effective in a later earthquake, many earthquake-proof shelters were built, and the economy of the area returned to nearly normal within a year.

Box 6.6. The Kashmir earthquake, Pakistan, 2005 – magnitude 7.6

Shazia Ahmed – a mother

'"I'm hungry!" These were the first words my daughter said to me when I pulled her out of the rubble that was once our house. I had never felt so much relief in my entire life. Although Umbreen was dusty and bruised, she was alive, and at that moment there could have been no greater miracle.

It had been three days of agonising terror before my husband and neighbours were able to rescue our baby. Three days of torture that only a mother could understand. I grabbed at her and frantically checked for any missing limbs, fingers or toes. I took her to the field hospital down the mountain and, aside from a few cuts and bruises, the doctors gave her a clean bill of health. It is a miracle that she is alive and well. …

Our 'village' is now comprised of only 200 or so tents at the base of the mountain. Everyone's house has been destroyed. Thankfully the staff of Sungi (an Oxfam local partner) came to help us out. Not only did they provide tents, blankets and clean drinking water, they provided a shoulder to lean on at a time we needed it most.

Sometimes you just need someone to listen and share in your grief.'

From: https://www.oxfam.org.nz/what-we-do/emergencies/previous-emergencies/kashmir-earthquake-2005/stories -from-balakot

Shazia with her baby, who survived for three days in the rubble at Balakot before being rescued

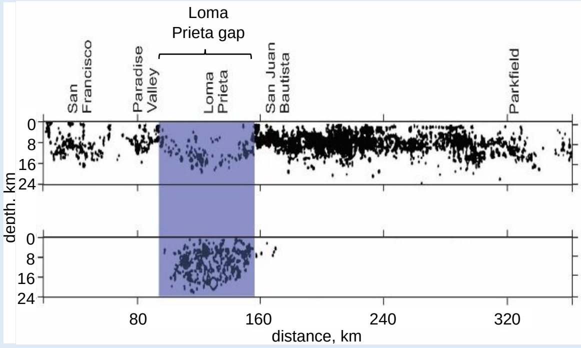
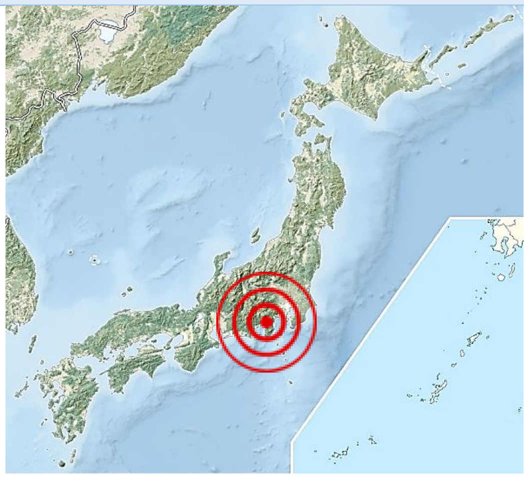
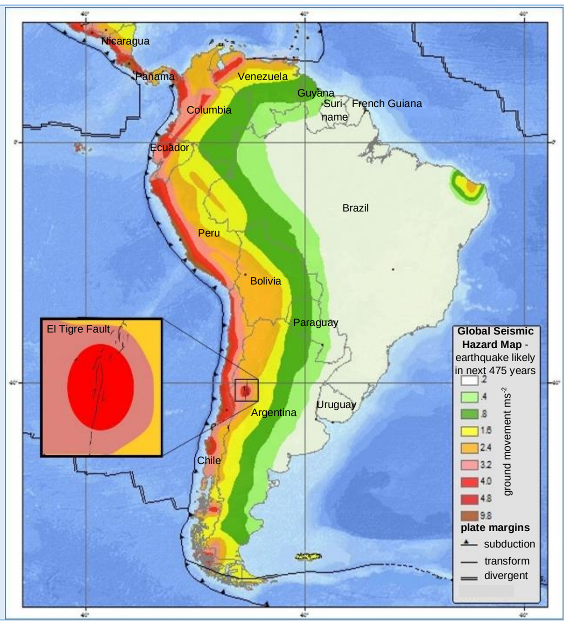
The devastated city of Balakot

The Kashmir earthquake hit northern Pakistan at 08.50 on the morning of 8 October, 2005. It was in the collision zone of the Eurasian and Indian tectonic plates which formed the Himalayan mountain range. The earthquake was one of the worst natural disasters ever to hit southern Asia. The estimated death toll was more than 85,000; the city of Muzaffarabad was hardest hit. Many more people were injured and 3.5 million people were made homeless. Many schools collapsed and hospitals and rescue services failed. Towns and villages were completely wiped out in remote mountainous areas. Roads blocked by landslides made it even more difficult for the rescue services. There were many strong aftershocks. Later satellite measurements showed that the land above the epicentre had risen by several metres.

There was a huge national and international rescue response immediately afterwards, but reconstruction of facilities in the region over the following months and years was slow.

In countries that can be hit by major earthquakes, the public must be protected. Protection measures include attempts to forecast (Table 6.6) and predict damaging earthquakes, constructing buildings that can withstand earthquakes, and having plans in place to deal with the earthquake effects.

Table 6.6. Methods of forecasting earthquakes

Earthquake forecasting method	Description	Image	Source
Seismic gap in space	Along major faults there are often areas with many earthquakes and other areas with few. Where there have been few earthquakes, tension may be building up, so that is where the next earthquake is expected		The Loma Prieta gap on the San Andreas Fault, California, USA. The upper diagram shows that there had been few earthquakes in the gap until the 'big one' and its aftershocks in 1989 – lower diagram
Seismic gap in time	Some earthquakes have a fairly regular time pattern – allowing the time of the next earthquake to be forecast		The Tōkai earthquakes in Japan have struck regularly, every 100-150 years, in 1498, 1605, 1707 and 1854. The next earthquake is forecast to be soon
Seismic hazard mapping	This uses all available data to show the areas of highest earthquake risk		Seismic hazard map of South America, prepared by the US Geological Survey

Earthquake forecasting methods can show when and where major earthquakes are likely. But earthquake prediction methods try to pinpoint the likely place and time more accurately. Several of these are being scientifically investigated, but none has so far been shown to be reliable. The methods include:

- monitoring ground uplift and tilting near faults
- measuring small earthquakes using seismometers in case these are 'foreshocks' before a big earthquake

- monitoring levels in water wells, in case increasing pressure causes groundwater to rise or increasing tension causes more fractures, when water levels fall
- checking on the emission of radon gas from the ground – in the build-up to an earthquake, small fractures may release more radon gas than usual, that can be detected in groundwater
- the ability of rocks to transmit electricity (their electrical resistivity) may change before an earthquake. The more water a rock holds the better it can transmit electricity, so if more fractures form before an earthquake, these fill with water and can transmit electricity more effectively (so lowering their resistivity to electrical currents).

Where buildings are built to resist earthquakes, and the earthquake-resistant building codes are enforced, damage can be greatly reduced and so can death tolls. Different methods used to help buildings resist earthquake damage are shown in Table 6.7.

Table 6.7. Building methods to resist earthquake damage

Earthquake-resisting method	Description		Image	Source
Strength during shaking	Earthquake waves move both up and down and sideways	Shear walls are made of panels that can shake without breaking		Shear walls built to give extra strength to a building, Oregon, USA
		Foundation bolts tie walls flexibly to foundations		Foundation bolts and straps, Napa, California, USA
Isolating during shaking	A wide range of methods can be used to separate buildings from shaking ground, including rubber shock absorbers, springs, wheels and ball bearings			Shake table testing base-isolation methods. The normal non-isolated building on the left is collapsing. University of California, San Diego, USA

Table 6.7. Building methods to resist earthquake damage, continued

Earthquake-resisting method	Description	Image	Source
Building with reinforced concrete	Reinforced concrete buildings are constructed with networks of rebar (reinforcing bar) – steel bars within the concrete that can stop the shaking causing the brittle concrete to fail		Rebar steel network for a concrete bridge foundation
Resistant water, gas and electrical mains	Gas and electrical mains can be fitted with devices that automatically cut off – to prevent fires; water mains with flexible joints resist damage, so that water supplies are not cut off during earthquake-caused fires		Automatic cut-off valve fitted to a gas main, Seattle, USA

In areas affected by earthquakes, plans should be put in place by the authorities to protect the population. These often have four phases: mitigation (reducing likely effects, for example, by the methods in Table 6.7), preparedness (including administrative planning, preparation and training), response (how the emergency services should react during and soon after the earthquake), and recovery (beginning to preserve and re-build the community).

Part of earthquake preparation is the training of pupils in schools and the wider public in what to do during and after an earthquake. The most important part of this is for each family, school, factory, office, etc. to develop their own plan.

Box 6.7. An earthquake plan

The Earthquake Country Alliance in California, USA, highlights *‘Seven steps to earthquake safety’*

Earthquake warning sign, Vancouver, Canada

Prepare

Step 1: Secure your space – make sure furniture, etc. won’t fall over dangerously
Step 2: Plan to be safe – make your own disaster plan and make sure everyone knows what it contains
Step 3: Organise disaster supplies – where they can be found easily
Step 4: Minimise financial hardship – by organising your documents, strengthening the building and taking out insurance

Survive and recover

Step 5: Drop, cover and hold on – protect yourself under heavy furniture during the earthquake
Step 6: Improve safety – leave the building if you can, help the injured and prevent other injuries
Step 7: Reconnect and restore – link up with others, repair damage and rebuild the community

6.1.3 Tsunami

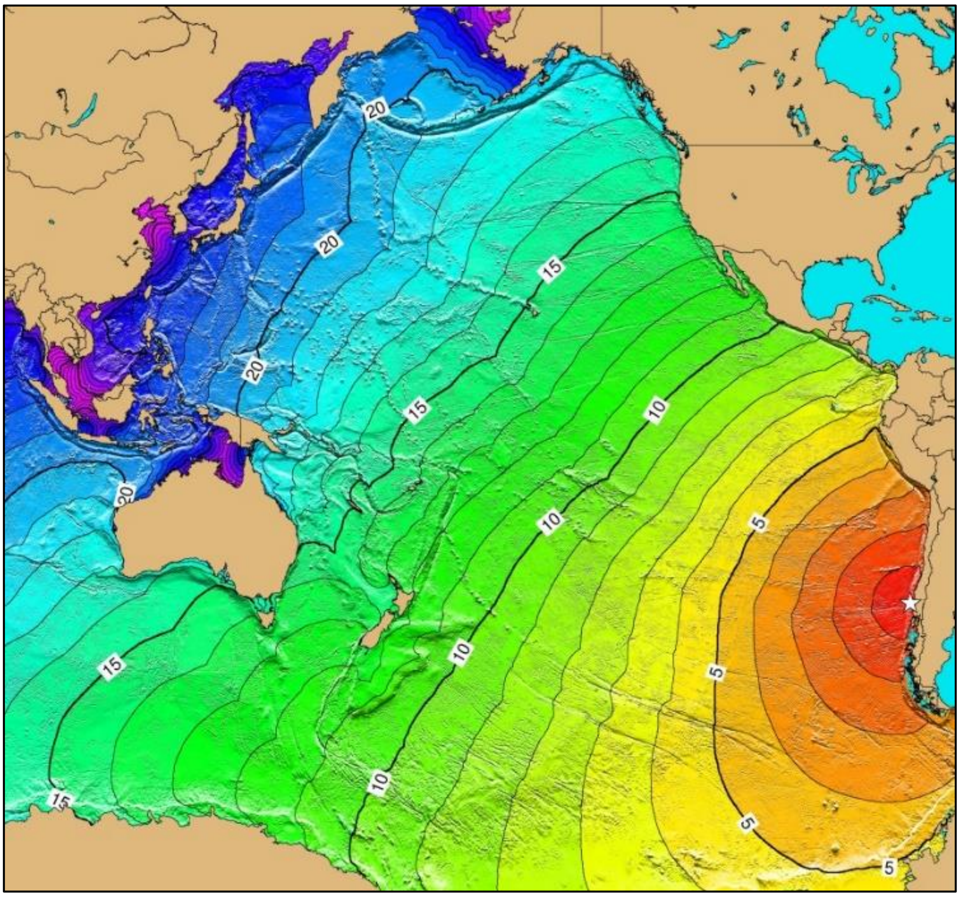
Tsunamis are large water waves caused by earthquakes, volcanic eruptions, landslides falling into water, or meteorite impacts; 'tsunami' means 'harbour wave' in Japanese. Tsunamis were called 'tidal waves' in the past, even though they have nothing to do with tides.

The height of tsunami waves reaching the coast depends upon the size of the triggering process and the shape of the coastline. In the open ocean, tsunami waves are low but travel at speeds of up to 800 km/hr^{-1}. As they reach shallower water near coastlines, friction slows down the base of the wave, causing it to become steadily higher. Shallow-sloping coastlines produce higher waves than steeply sloping coasts. The largest tsunami waves can reach heights of more than 40 metres, the height of a 12-storey building.

It is not just the wave height that is damaging, but when tsunamis reach land enormous volumes of water can flow onshore. These can flow up to 10 km inland sweeping everything that is not tied down with them. This is why so many people can be killed by tsunamis.

Large tsunami waves can travel across wide oceans. The most powerful earthquake ever recorded, the 1960 Valdivia earthquake in Chile, caused a tsunami that travelled right across the Pacific Ocean, devastating the island of Hawaii on the way, and reaching New Zealand, Australia, the Philippines, Japan and China (Fig 6.4).

Figure 6.4. The tsunami caused by the 1960 Valdivia earthquake, showing travel times in hours across the Pacific Ocean



Details of some large and devastating tsunamis are shown in Table 6.8.

Table 6.8. Large tsunamis and their effects

Tsunami	Description	Image	Source
2011 Tōhoku, Japan tsunami	A magnitude 9.0 earthquake offshore caused the tsunami, resulting in more than 15,000 deaths and the meltdown of the Fukushima nuclear power station, with the evacuation of hundreds of thousands of residents (Table 6.5 above)		The Tōhoku, Japanese tsunami; black smoke from a damaged oil refinery
2004 Indian Ocean tsunami	230,000 people were killed in Indonesia and other Indian Ocean coastal countries, including Sri Lanka, India and Somalia (Table 6.5 above)		The 2004 tsunami at Ao Nang, Krabi Province, Thailand
1883 eruption of Krakatoa	More than 36,000 deaths were caused by the Krakatoan eruption tsunami		The result of the tsunami caused by the 1883 Krakatoan eruption
1755 Lisbon, Portugal earthquake	More than 40,000 deaths caused by the earthquake, tsunami and fires; the Portuguese capital, Lisbon, was almost completely destroyed		An artist's view of the 1755 Lisbon earthquake and tsunami

Box 6.8. The 2011 tsunami, Tōhoku, Japan

On Friday, 11 March, 2011, the most powerful earthquake ever recorded in Japan (magnitude 9.0) triggered a major tsunami that reached heights of 40 metres and flowed 10 km inland. This is the story of school children in the Unosumaicho district, recorded by reporters Sho Komine and Yasushi Kaneko of the Yomiuri Shimbun national newspaper in Japan.

Public hospital in Minamisanriku after the 2011 tsunami

"Tsunami hit the Unosumaicho district in Kamaishi, with floodwaters reaching the third floor of Kamaishi-Hogashi Middle School and the nearby Unosumai Primary School. Before the latest earthquake, the two schools jointly had conducted disaster exercises. At the middle school the announcement system malfunctioned right after the earthquake and became unable to broadcast evacuation calls. However, students were able to quickly leave the building and gym as they had practised, and grabbed the hands of primary school students – who were also on the verge of escaping from the building – and together ran up to higher ground." "One middle school first-grader, Dai Dote, 13, held the hands of two third-grade primary school girls [8 years old]. On their way up the hill, one of the girls cried and started hyperventilating, while the other became unable to speak. "It's OK," Dote told the girls as they ran to the top of the hill, more than two kilometres from their schools. Once confirming the safety of all their friends, the girls looked relieved, Dote said." One teacher told the Yomiuri Shimbun, "I've repeatedly told children in class that we might experience tsunami larger than ever expected. It's almost a miracle that this many children were saved. I'm proud of the children for making [lifesaving] decisions on their own."

Box 6.9. The Indian Ocean tsunami, 2004

On the 26 December (the day after Christmas/Boxing Day) in 2004, 11-year-old English schoolgirl Tilly Smith was on the beach with her father, mother and younger sister in Phuket, Thailand.

Later, she told her story to a reporter.

Tsunami wave striking the Phuket coast

Box 6.9. The Indian Ocean tsunami, 2004, continued

Tilly's story:

"I remembered that I had been taught it in a geography lesson. It was the exact same froth, like you get on a beer, it was sort of sizzling. I said, 'There's definitely going to be a tsunami, and my Mum didn't believe me, and so she kept on walking. But my Dad sort of believed me and Holly, my sister, was getting really scared. So she ran back to the pool [at the hotel] and my Dad went back with her. And then I said, 'Right Mum, I'm going, I'm definitely going, there is definitely going to be a tsunami. And she just, 'Hmmm – 'bye then'. So I went back and she was reacting a bit more when I'd gone, and so she went back to see if I was OK. And in the minute she had come back, the water started coming up the beach.

"Well, I told my Dad and my Dad told the security guard and the security guard told the people on the beach. There were quite a few families on the beach, just in the water.

"If it wasn't for Mr Kearney (my geography teacher), then I'd probably be dead and so would my family. And so I'm quite proud that he taught me that in time.

"My Mum didn't realise because she wasn't taught about tsunamis when she was younger and didn't realise what a tsunami was. She didn't even know that word existed. So I think it's really good to actually know the word and be taught it."

Tilly's family went upstairs in the hotel and watched as the tsunami waves filled the swimming pool with debris. Tilly may have saved nearly 100 lives on the beach that day, a day when more than 8,000 people died in Thailand alone.

The National Tsunami Hazard Mitigation Program in the USA has the three parts shown in Figure 6.5, warning guidance, mitigation, and hazard assessment, as in Table 6.9.

Figure 6.5. The logo of the US National Tsunami Hazard Mitigation Program

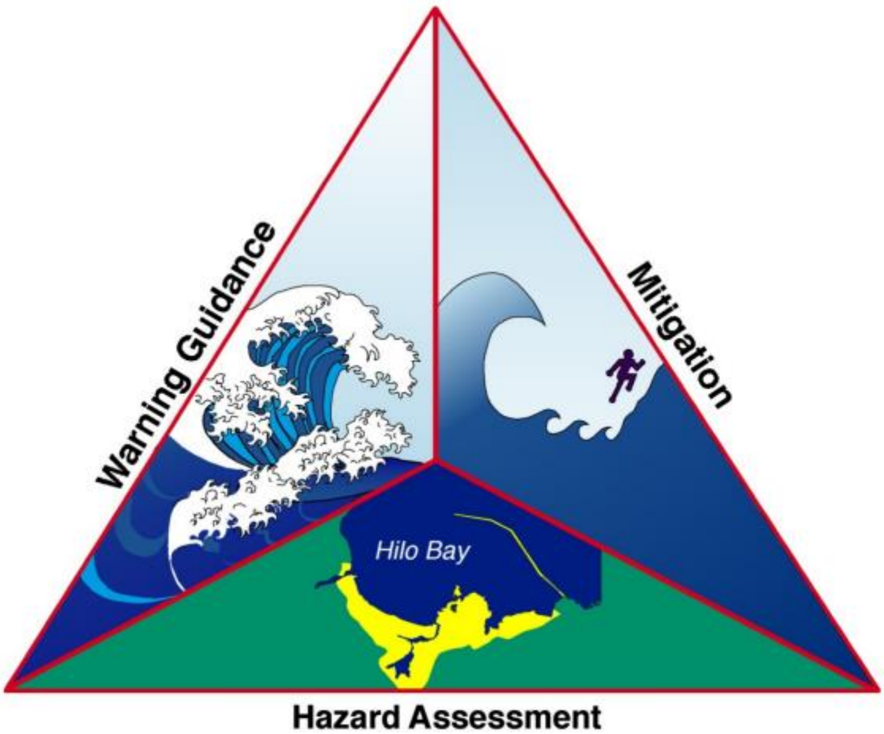
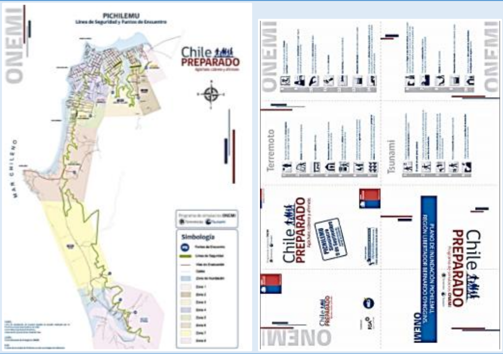
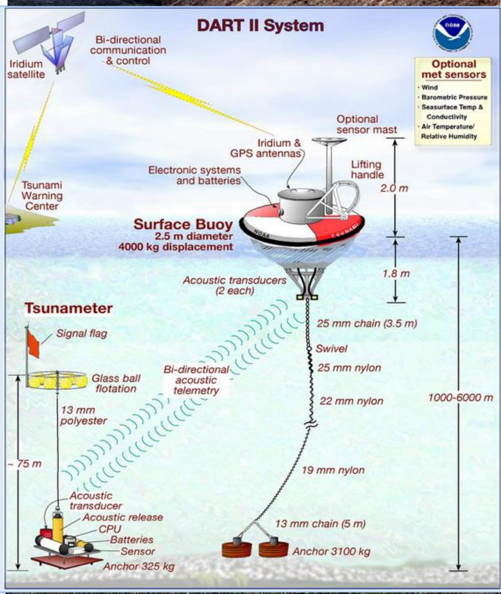


Table 6.9. Methods used to increase safety during tsunamis

Tsunami-safety method	Description	Image	Source
Hazard assessment	Likely hazards are assessed and the results published to help the community. This Chilean warning leaflet has information about tsunami risk zones, meeting points, emergency care areas and evacuation routes		Tsunami hazard warning leaflet for the coastal city of Pichilemu in central Chile
Mitigation	Tsunami hazards are reduced by building tsunami walls		A tsunami wall at Tsu-shi in Japan
Warning and guidance	The Deep-Ocean Assessment and Reporting of Tsunamis (DART) system is based on a series of buoys across oceans, which detect pressure changes caused by tsunamis, so that early warnings can be issued		The DART II buoy and network warning system
	The public is trained in what to do when warnings are heard, while information is published in leaflets and on signs		Tsunami warning sign, Okumatsu-shima, Japan, with evacuation routes

Box 6.10. Tsunami warning information

A tsunami mitigation fact sheet, published online in the USA, contains this guidance.

In general, if you think a tsunami may be coming, the ground shakes under your feet or you hear there is a warning, tell your relatives and friends, and **move quickly to higher ground.**

Important Facts to Know about Tsunamis

- Tsunamis that strike coastal locations in the Pacific Ocean Basin are almost always caused by earthquakes. These earthquakes might occur far away or near where you live
- Some tsunamis can be very large. In coastal areas their height can be as great as 30 feet (9m) or more (100 feet (30m) in extreme cases), and they can move inland several hundred feet (10s – 100s of metres)
- All low-lying coastal areas can be struck by tsunamis
- A tsunami consists of a series of waves. Often the first wave may not be the largest. The danger from a tsunami can last for several hours after the arrival of the first wave
- Tsunamis can move faster than a person can run
- Sometimes a tsunami causes the water near the shore to recede, exposing the ocean floor
- The force of some tsunamis is enormous. Large rocks weighing several tons, along with boats and other debris, can be moved inland hundreds of feet by tsunami wave activity. Homes and other buildings are destroyed. All this material and water move with great force and can kill or injure people
- Tsunamis can occur at any time, day or night
- Tsunamis can travel up rivers and streams that lead to the ocean

If you are on land:

- Be aware of tsunami facts. This knowledge could save your life! Share this knowledge with your relatives and friends. It could save their lives!
- If you are in school and you hear there is a tsunami warning, you should follow the advice of teachers and other school personnel
- If you are at home and hear there is a tsunami warning, you should make sure your entire family is aware of the warning. Your family should evacuate your house if you live in a tsunami evacuation zone. Move in an orderly, calm and safe manner to the evacuation site or to any safe place outside your evacuation zone. Follow the advice of local emergency and law enforcement authorities
- If you are at the beach or near the ocean and you feel the earth shake, move immediately to higher ground. DO NOT wait for a tsunami warning to be announced. Stay away from rivers and streams that lead to the ocean as you would stay away from the beach and ocean if there is a tsunami. A regional tsunami from a local earthquake could strike some areas before a tsunami warning could be announced
- Tsunamis generated in distant locations will generally give people enough time to move to higher ground. For locally generated tsunamis, where you might feel the ground shake, you may only have a few minutes to move to higher ground
- High, multi-storey, reinforced concrete hotels are located in many low-lying coastal areas. The upper floors of these hotels can provide a safe place to find refuge should there be a tsunami warning and you cannot move quickly inland to higher ground. Local Civil Defense procedures may, however, not allow this type of evacuation in your area. Homes and small buildings located in low-lying coastal areas are not designed to withstand tsunami impacts. Do not stay in these structures should there be a tsunami warning
- Offshore reefs and shallow areas may help break the force of tsunami waves, but large and dangerous waves can still be a threat to coastal residents in these areas. **Staying away from all low-lying areas is the safest advice when there is a tsunami warning**

6.1.4 Landslide

Landslides strike when rock fails, and rock failure can be triggered by earthquakes, eruptions, storms or because the rock has become weakened in some way. Landslides into water can, in their turn, trigger tsunamis.

Landslides, also called **landslips**, include several different types of falls, slides and flows that can happen catastrophically quickly but also very slowly. Even slow landslides are damaging (Table 6.10). They can be on land or under water.

Table 6.10. Different types of falls, slides and flows

Rock failure type	Description	Image	Source
Rockfall	Rocks topple or fall due to gravity, catastrophically fast		Rockfall, Scarborough Headland, North Yorkshire
Slide	The rocks collapse as a mass and not as individual blocks, catastrophically fast		Rockslide at Oddicombe beach, Devon
Slump	Slumps are movements of material down a slope as one mass. Some slumps are catastrophically fast while others have very slow creep; some slumps are rotational, when the sloping surface tilts backwards as the block slides down along a curved scar		Rotational slumps on the larger slumped area of the old road, Mam Tor, Derbyshire

Table 6.10. Different types of falls, slides and flows, continued

Rock failure type	Description	Image	Source
Rock flow	Rock flows include debris flows and debris avalanches; because they contain a lot of water, they flow at high speeds of up to tens of km per hour, especially down steep slopes and valleys		Debris flow onto the beach at Trimingham, Norfolk
Creep	Surface materials like soil creep slowly downhill, either as rounded masses or forming series of small terraces, that are often later used as paths by farm animals		Soil creep on the side of the Cuckmere valley, East Sussex
			Terracettes below Morgan's Hill, Wiltshire

Some of the most damaging global landslides are shown in Table 6.11.

Table 6.11. Major landslides

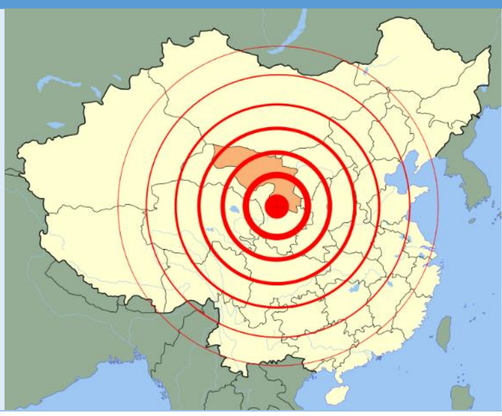
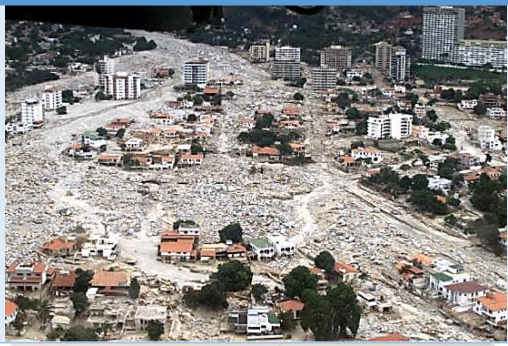
Major landslide	Description	Image	Source
Haiyuan landslides, December 1920	The landslides were triggered by the 7.8 magnitude Haiyuan earthquake (recorded in China as 8.5 magnitude) on 16 December 1920 (Table 6.5). Slopes of unstable fine-grained silt (loess) collapsed causing more than 600 landslides, with a total death toll of more than 100,000		The 1920 Haiyuan earthquake which triggered the Haiyuan flows in central China

Table 6.11. Major landslides, continued

Major landslide	Description	Image	Source
Vargas flows, Venezuela, December 1999	On 15 December 1999, torrential rain triggered a series of debris flows, killing more than 30,000 people, destroying many homes and causing the state facilities to collapse; whole towns disappeared and homes were swept into the sea		Wide-spread destruction in the Caraba-lleda area caused by a 6m thick debris flow
Nevado Huascarán debris fall, Yungay, Peru, May 1970	An inscription on this ruin reads: "A town where 35,000 people lived stood here; under an earthquake and a subsequent landslide from Huascarán [the volcano, in the background] here's just a stone debris [sic]. It all happened within a few minutes on May 31 1970."		Photo taken at Yungay, ten years after the tragedy – the building with the inscription
Khait landslides, Tajikstan, July, 1949	Hundreds of landslides were triggered by the 7.4 magnitude Khait earthquake; fine-grained silt saturated with water flowed at more than 30m/sec^{-1} killing around 4000 people in Khait, and some 28,000 people in the surrounding areas		The scar on Chokrak mountain and the landslide that destroyed Khait village

Landslides can be catastrophically sudden, with no time for people to evacuate their homes, resulting in many deaths.

Box 6.11. The Oso mudflow, 29 March 2014

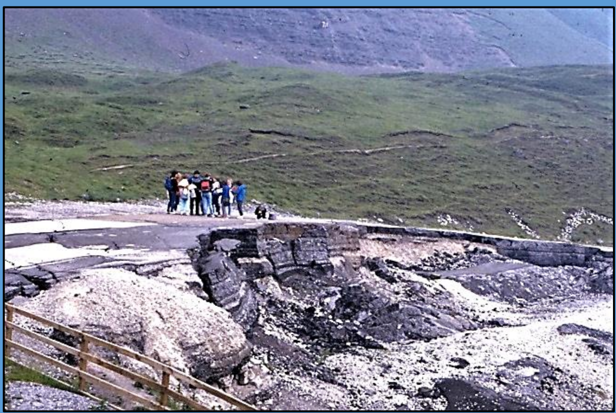
The most damaging landslide in the history of the USA destroyed around 50 homes, killing 43 people, near Oso in the Cascade Mountain region of Washington State, near Seattle. A hillside saturated with water collapsed producing a massive mudflow. Eyewitnesses described a wall of mud, perhaps eight metres high, racing across the valley towards them with the sound of freight trains, plane crashes and "tens of thousands of things hitting each other". Heavy rainfall in the weeks beforehand may have destabilised the slope.

Box 6.1E. Slumping and sliding on Mam Tor

The landslide at Mam Tor in Derbyshire started several thousand years ago and continues to move today. A cross-Pennine road was built across the landslide in 1812 and later became the A625, even though it was continually being broken as the land beneath it slipped, at a rate of up to 20cm per year near the road. Many layers of tarmac were added to mend the road (visible in the foreground – left image), but it was finally closed completely in 1979 after a very wet winter.

Why is the land slipping so dramatically? Mam Tor consists of interbedded sandstones and shales (seen in the background of the left image) but these are underlain by thick, dark shales, containing much pyrite (FeS_2). When exposed to air and water, the pyrite breaks down to produce acids which weaken the shales. Once the water table within the rock is raised by heavy winter rainfall, the pressure of water in the pore spaces increases until friction between the particles of rock is reduced and the rock gives way.

Most slippage occurs along curved slip planes. These are seen on a small scale in the slipped, tilted blocks of tarmac (which show how many times Derbyshire County Council tried to patch up the old A625). On the larger scale, the hummocky land in the middle ground once formed the summit of Mam Tor; as it slid down it resulted in the formation of the cliff face behind it.



The Mam Tor landslide in 1985. The pupils are standing on the surface of the old A625 road

The old A625 across the Mam Tor landslide, Peak District, Derbyshire

Peter Kennett

A number of methods are used to reduce landslide risk. These range from mapping and monitoring hazards, through warning systems, to different ways of preventing landslides or reducing their effects, as in Table 6.12.

Table 6.12. Landslide and rockfall risk reduction methods

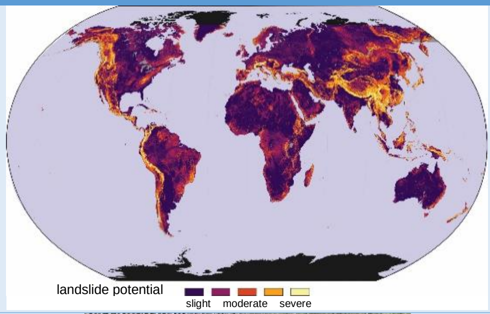
Landslide risk reduction	Description	Image	Source
Hazard mapping	Landslide hazards are mapped at local to global scales. The NASA map shows that the most dangerous regions are in active climatic and tectonic areas, including plate margin mountain zones		Global landslide hazard map compiled by the US National Aeronautics and Space Administration (NASA)
Monitoring	Slopes likely to fail are monitored by a range of devices, including wireline extensometers, seismic geophones and rain gauges, and by measurement of underground water pressures		Slope stability equipment near Sprey Point, Holcombe, Devon
Building codes and warning signs	Building codes (when enforced) prevent buildings being constructed in highly hazardous areas, while warning signs warn both traffic and the general public		Traffic warning sign on Marine parade, Shaldon in Devon
Slope reduction and terracing	Hazards are reduced by making slopes shallower and by excavating series of horizontal terraces at intervals; the terraces reduce the height of rock walls and catch debris		Roadside rock terracing with rock bolting near Sidmouth, Devon
Drainage	Drains are sited at the tops and bottoms of slopes as well as within slopes, to remove water quickly, reducing the chance that increased water pressures will trigger a landslide		Drainage channel behind sea wall defences near Larkholm, Fleetwood, Lancashire

Table 6.12. Landslide and rockfall risk reduction methods, continued

Landslide risk reduction	Description	Image	Source
Planting	Trees or other plants are planted so that their roots bind loose materials together and remove water, helping to stabilise slopes		Tree planting to stabilise a road embankment. The A120 near Stebbingford, Essex
Removal of loose surface materials and rock bolting	Loose debris is removed and larger slabs and other loose materials are attached to the slope by long rock bolts		Rock bolts at Black Rock on the coast of Sussex
Coverage by wire netting and geotextiles	These are fastened over the slope to prevent the falling of debris  Geotextile samples		Wire mesh attached with rock bolts over a crumbling rock face, near Teignmouth, Devon
Shotcrete coverage	A layer of cement is sprayed over loose rock faces to bind them together and stabilise them		A cutting stabilised by shotcrete at Brincliffe, Sheffield, South Yorkshire

Table 6.12. Landslide and rockfall risk reduction methods, continued

Landslide risk reduction	Description		Image	Source
Cuttings and faces protected by walls and gabions	The bottoms of unstable slopes are protected to reduce possibilities of sliding and slumping and to prevent erosion	Walls are constructed of natural stone or concrete to protect faces		Retaining wall under repair in Knutsford, Cheshire
		Gabions are wire mesh boxes filled with rocks; the mesh is galvanised for protection		Slope stabilised with gabions in a supermarket carpark in Sheffield, South Yorkshire
Barriers	Barriers are built to catch debris, leaving space for it to build up behind the barriers			Barriers used to catch boulders on Ecclesall Road, Sheffield South Yorkshire
Protection shelters	Shelters are built to protect transport routes and public areas from falling debris			Rock protection shelter over the road and railway on the Kyle of Lochalsh to Lochcarron Road in Highland Region, Scotland
Concrete buttresses and rip rap	Concrete buttresses are built and large boulders of rip rap are dropped at the foot of slopes likely to fail or be eroded by river or coastal currents			Rip rap boulders dropped on the coast in East Sussex, to protect Fairlight village above

6.2 Environmental issues

Humans affect the environment at all scales from local to global. We often get used to these changes and so don't see them as problems for the environment. Major changes include the building of settlements and the farming of wide regions. So the environments of many parts of the Earth today are very different from their original wild states. Indeed, the impact of human activity has been recorded in nearly all environments on Earth, from the deepest seas to the highest mountains, and from the poles to shallow tropical seas.

6.2.1 Erosion

Figure 6.6. Footpath erosion, south of Thornthwaite Beacon, Hartsop, Cumbria.

Whenever you walk along a footpath, there is the danger of causing erosion, especially if many other people use the path as well (Figure 6.6).

The only ways of preventing this erosion by the public are to close or re-route the path or to strengthen it by laying stone or timber walkways.

Meanwhile, when soils are exposed by poor farming methods or when vegetation is burnt off, the soil can readily be eroded by water and wind (Table 6.13).

Table 6.13. Soil erosion

Soil erosion	Description	Image	Source
Soil erosion by water	In sloping areas not protected by vegetation, soil erosion can form deep gullies that are very difficult to reclaim once they have formed; these gullied areas are called badlands		Soil erosion in the Otter Valley, Devon
Soil erosion by wind	Wind erosion can remove huge amounts of soil as dust		Wind erosion of dust across the Fens, called locally a fen blow, across Hod Fen Drove near Yaxley, Cambridgeshire
	Poor farming methods in the 1930s in the Great Plains area of central USA led to soils breaking down; so, when there was drought in the 1930s, huge amounts of soil were eroded in the American 'dust bowl' regions		Farm machinery buried by windblown dust, Dallas, South Dakota, USA, 1936

Good farming practices to preserve soils include:

- not ploughing up and down slopes but ploughing across slopes in contour ploughing; this stops water rushing downhill in rainstorms; the water sinks into the soil instead
- planting trees in gullies, so that their roots bind the soil together
- ensuring soil is covered by crops for as much of the year as possible, particularly during windy seasons
- planting lines of trees and hedges as windbreaks to reduce wind erosion
- adding nutrients to the soil in fertiliser so that crops continue to grow
- making sure that vegetation is not overgrazed and soil over-compacted by animals.

Coasts are eroded naturally as tides move waves up and down beaches, particularly during storms. This is not a problem unless it affects areas where people are living, where there are coastal communications, or where beaches are used by tourists. Different methods of reducing coastal erosion are shown in Table 6.14.

Table 6.14. Methods of reducing coastal erosion

Coastal erosion-reduction	Description	Image	Source
Groynes	Groynes are barriers of timber, boulders or concrete built across beaches to reduce movement of sediment along the beach. The sediment builds up on one side, producing a series of short curved beach areas		Rocky groyne at Hengistbury Head, near Mudeford, Dorset
Sea walls	Sea walls are built of large boulders, cut stone which may be cemented, or concrete to protect coastal areas		Curved seawall used to deflect waves away from land at Leasowe, Wirral, Merseyside
Rip rap	Boulders of rip rap placed in eroding areas		Rip rap protecting the coast at Dawlish Warren, Devon
Tetrapods	Large concrete structures specially designed to break the force of waves		Tetrapods protecting a sea wall at Ventnor, Isle of Wight

One of the problems of reducing erosion on one part of the coast is that the area may have been the source of sediment for other areas further along the coast. So, when one area of the coast is protected, erosion can increase at other nearby areas. This highlights how, in dynamic coastal areas, coastal engineering can have 'unforeseen consequences' elsewhere.

6.2.2 Drainage-changes

Most buildings and other constructions channel rainwater. As soon as rainwater reaches channels it flows faster and is more likely to cause erosion. So buildings require gutters, gutters need special channels or storm drains to be built, and the rivers these drain into must be engineered to reduce erosion (Figure 6.7). All this has the effect that rainwater is channelled away from built areas and cannot sink into the ground to recharge aquifers. But it can also cause flash flooding downstream. This problem is being tackled in some areas by not concreting or tarmacking over everything, but instead deliberately leaving areas for rainwater to sink into the ground

Figure 6.7. The Malago storm relief drain, near Bristol. Avon.

6.2.3 Waste disposal

Humans produce enormous amounts of waste. The World Bank has estimated that, averaged across the Earth, each person produces more than 1kg of waste per day, but this is uneven, some regions producing far more waste than others.

Many people put their waste into a bin and do not think any further about what happens to that waste. But all waste needs to be managed. Methods of waste management differ from region to region (Figures 6.8 and 6.9) and have changed over time, but modern methods usually involve the 'three Rs' of 'reduce, reuse and recycle'. This aims to extract the greatest value from the waste and dispose of the minimum amount of material.

Figure 6.8. Waste management in Kathmandu, Nepal

Figure 6.9. Waste management, Sheffield, South Yorkshire.

However much material can be reused and recycled, some will eventually have to be dumped. The major types of waste that must be dumped are shown in Table 6.15.

Table 6.15. Waste materials needing disposal

Waste material	Description	Image	Source
Inert waste	Inert waste is chemically un-reactive waste; this includes building rubble and material from demolished buildings. However, this may still contain some chemically reactive material like paper, timber and plasterboard, and hazardous materials like asbestos		Inert building waste at a waste transfer station, Ince-in-Makerfield near Wigan, Greater Manchester
Domestic waste	Domestic waste is household waste containing a wide range of materials; as it decays it produces a toxic liquid called leachate and releases gas, including methane		Domestic waste dump at Dogsthorpe, Peterborough, Cambridgeshire
Toxic waste	Toxic waste is solid or liquid chemically reactive waste that can be harmful if swallowed, inhaled or absorbed through the skin. It includes paint, oils and a wide range of chemicals and is most commonly disposed of in impermeable landfill sites		The Valley of the Drums toxic waste site, Kentucky, USA in the 1980s; sites like this changed environmental law in the USA
Radioactive waste	Radioactive waste continues to release damaging radiation for thousands of years or more. It is usually divided into low-, medium- and high-level waste; low-level waste can be buried near the surface, but high-level waste needs deep burial		Drigg low level radioactive waste repository near Sellafield, Cumbria (taken from the air)

Domestic and toxic wastes are properly disposed of in specially prepared sites. The best sites are old quarries and brick pits in impermeable rocks, although hollows in impermeable land surfaces are also used. The impermeability stops liquid **leachate** trickling down into the groundwater and gases escaping into the walls of the pit. In more permeable sites, the rocks can be lined with expensive impermeable plastic membrane (Figure 6.10). In areas where there are no hollows or quarries, landfill can be built into low hills before landscaping and capping.

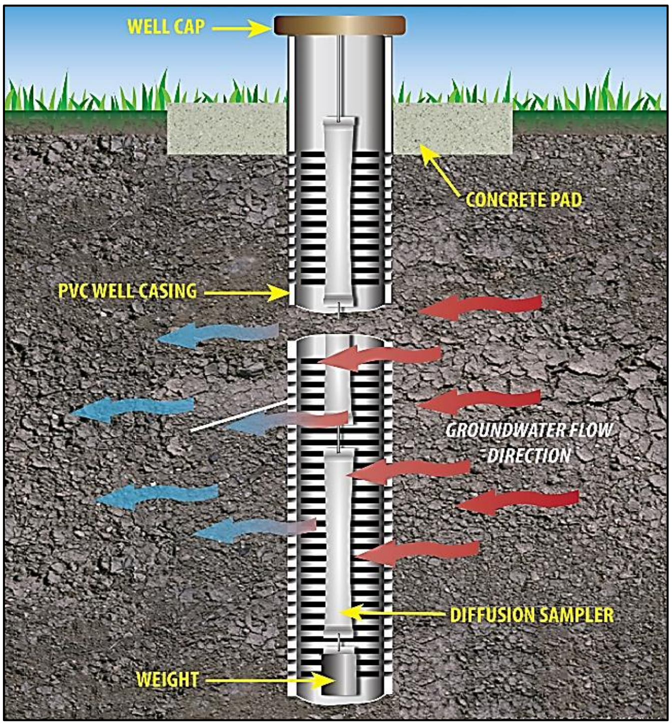
Figure 6.10. Laying black membrane as part of landfill site preparation, Drummond Moor, Howgate, Midlothian, Scotland

When landfill sites are full, they are carefully shaped and then capped with clay or other impermeable material to keep out the rainwater that might flush leachate out. Then they are covered with topsoil and methane vents are added, to allow gas to escape. Finally, they are planted with grass or other vegetation to help the site to blend in with the surrounding area. In some sites the methane is collected and used to produce energy, thus reducing its contribution to the greenhouse gases in the atmosphere.

Figure 6.11. Methane gas vents on an old landfill site, Shaw Forest Park, Swindon, Wiltshire

Finally, in well managed landfill sites, boreholes are drilled into the surrounding rocks and monitored for groundwater pollution (Figure 6.12).

Figure 6.12. Diagram of a typical groundwater monitoring well



6.2.4 Pollution

Pollutants are waste materials contaminating the environment. Three factors affect their polluting power: their chemical makeup, their concentration, and their persistence (how long they remain toxic).

Groundwater can be polluted by leakage from landfill sites but also by a range of industrial and agricultural processes, as shown in section 4.2.3.3. In these situations monitoring by groundwater wells like that in Figure 6.12. is very important.

Similar processes can also contaminate surface water, which is why water for human and industrial use should be treated before use.

Box 6.12. Acid mine drainage

A problem in old mining areas occurs when pumping of water from the mines stops, and they fill up with oxygenated water. This reacts with the mine minerals, dissolving them and bringing them to the surface as very acid, iron-rich water that can kill all life in any streams it reaches. Since the mine is out of business, there are often no funds for dealing with this expensive problem, and it has to be tackled by local authorities.

Acid drainage from an old coalmine, Ecclesall Woods, Sheffield, South Yorkshire

A wide range of other types of pollution is recognised, in addition to surface and groundwater pollution. This includes:

- air pollution – chemicals, gases and particles like soot released into the atmosphere
- soil contamination – industrial and agricultural chemicals leaking into the soil
- littering – the public dropping litter and illegal dumping
- light pollution, particularly from street lights – people living in urban areas see fewer stars in the night sky than can be seen in darker areas

- thermal pollution – particularly water coolant from power stations heating local waters
- noise pollution – including road, aircraft and industrial noise
- visual pollution – from mines and quarries (see below) but also power lines, advertising hoardings, wind farms, waste dumps and derelict industrial sites
- marine pollution – from both treated and untreated waste being dumped at sea.

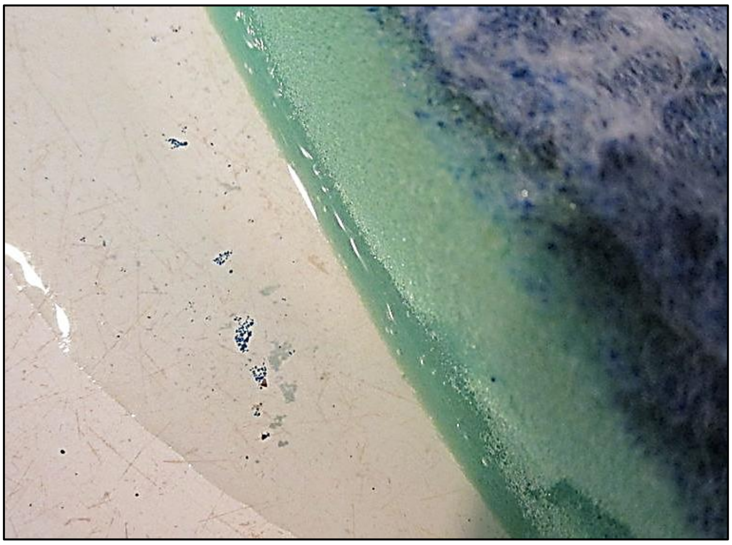
Recently pollution has been dealt with by ‘the polluter pays’ principle, that those who pollute should pay for the clean-up operations. Nowadays this is usually built into the contracts of possible polluting industries and mining and quarrying operations; but where the polluter cannot be found, this is not possible.

It is very difficult to find the polluter in marine areas, where there are three main sources of pollution: direct flow of pollution into the oceans; run-off of rain through streams and rivers; and pollutants from the atmosphere. Pollutants can flow directly into the sea as sewage from sewers or as industrial waste, including mine wastes. Run-off brings pollution from construction of buildings, roads and harbours and from agricultural soils, fertilisers and pesticides. Atmospheric pollution includes vehicle pollution, windblown dust and debris blown from landfill sites. Increasing levels of carbon dioxide in the atmosphere appear to be acidifying oceans, impacting particularly on coral reef communities.

Oil is a major ocean pollutant, most famously from major oil spills. However, most ocean oil pollution comes from tankers pumping out waste water, from leaking pipelines or by oil thrown down drains on land.

Plastic debris is a major problem because plastic decays so slowly. Tiny microplastic beads are used in many kitchen scrubs, toothpastes and cosmetics and have now been found polluting marine environments from coastal areas to deep sea trenches. Sea animals eat these in their food and it has been estimated that more than a third of the fish in the English Channel are contaminated with these beads. They have now been banned in several countries and it is hoped that they will be phased out worldwide very soon.

Figure 6.13. Microplastic beads released by a scouring sponge in a white bowl; microbeads range from a millimetre to a hundredth of a millimetre in size



6.2.5 Mining/quarrying

In the past, mines and quarries visually polluted many areas of the world, also causing water, air and noise pollution. Nowadays, in most parts of the world, there are tight environmental controls, with a range of methods used to reduce pollution, as in Table 5.7. Meanwhile many old mining areas have been built upon, while old quarries have become country parks and nature reserves. Old quarries can provide a wide range of ecological niches, like rock faces and ponds, not normally available to wildlife in the region, making them attractive to nature and the public alike.

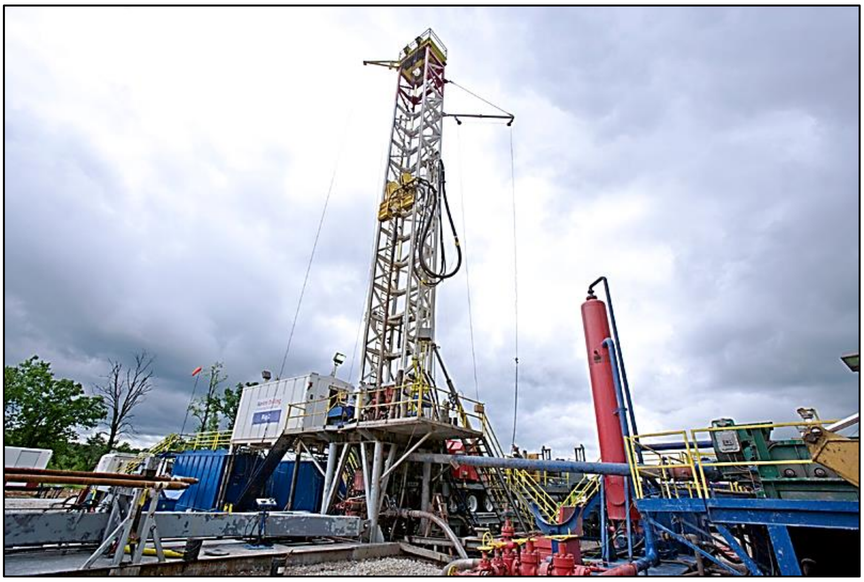
Figure 6.14. Country park in an old gritstone quarry with examples of some of the machinery used there when the quarry was in operation. Tegg's Nose Country Park near Langley, Cheshire

6.2.6 Burning fossil fuels and the greenhouse effect

Many scientists think, as discussed in Section 4.3.3 on atmospheric change, that the burning of fossil fuels is contributing to the increasing amounts of carbon dioxide in the atmosphere, and this in turn is contributing to climate change. Burning fuel does release carbon dioxide, with coal releasing almost twice as much carbon dioxide as natural gas (see Figure 5.6). However, other industrial processes also release carbon dioxide, particularly the manufacture of cement from limestone.

Research is currently being carried out to investigate whether the carbon dioxide formed by these processes can be 'captured' and pumped into old oil or gas fields and so not released into the atmosphere. The research is showing that '**carbon capture**' (or 'carbon capture and storage', CCS) is possible, but also that it is expensive. So there is, so far, no large-scale carbon capture operation running anywhere across the globe (Figure 6.15).

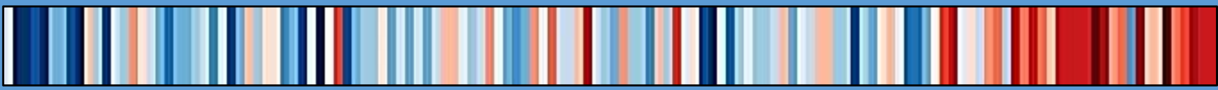
Figure 6.15. Carbon capture technology being tested at a coalmine



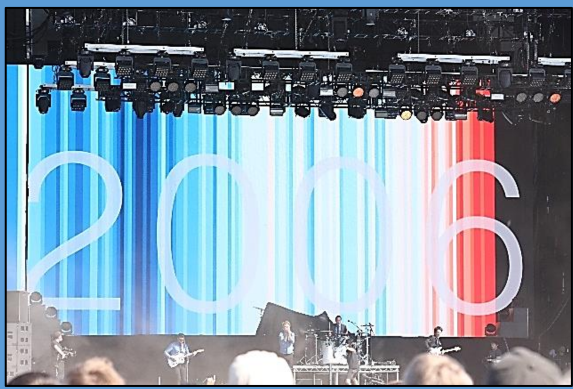
Box 6.2E. A new way to show climate change – climate warming stripes

Professor Ed Hawkins at Reading University has devised a new way of showing global and local climate change on Earth from the late 1800s onwards. He takes the mean temperature of each year and changes that to a colour, from the coldest blue to the hottest red.

The result from 1884 to 2019 for the UK is like this:



This clearly shows the warming trend, particularly in the last 20 years. It was used at the 2019 Reading Festival to show this trend dramatically, as a stripe was added year by year.



This method can be used for any set of climate statistics in any country or region, or for the whole world mean annual temperature.

Chris King

6.3 Impact on human history

The impact of geoscience on the course of human history is often difficult to see because many other factors were operating at the same time. Nevertheless, there are examples where Earth processes have had critical effects.

Box 6.13. The end of the Minoan civilisation

The Minoan civilisation, based on the island of Crete in the Mediterranean Sea, may have been the first major civilisation in Europe. It ran from around 6600 to 3400 years ago and its collapse may have been caused by the eruption of the nearby volcanic island of Thera (called Santorini today).

The Thera eruption had a Volcanic Explosivity index (VEI) of 6 or 7 and was one of the largest eruptions in recorded history. It destroyed the island of Thera (Santorini), leaving a huge crater and burying the Minoan city of Akrotiri under layers of volcanic ash. A tsunami caused by the eruption seems to have destroyed many Minoan coastal towns, possibly accompanied by earthquakes. It may be that the eruption weakened the Minoans so much that the Mycenaean people, who came afterwards, easily conquered them.

Satellite view of the Thera (Santorini) crater today

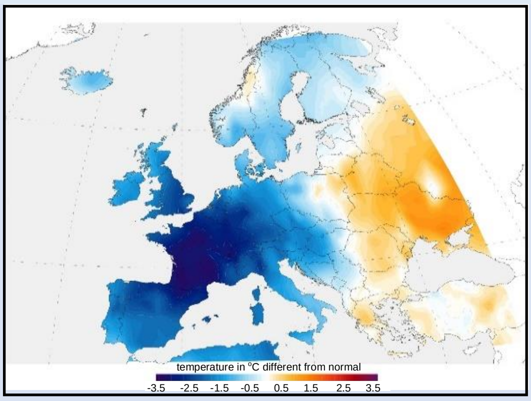
Box 6.14. ‘The year without summer’, 1816

1816 was a catastrophic year for farming across the world, causing tens of thousands of people to die of hunger. This global disaster is thought to have been caused by the eruption of Mount Tambora in Indonesia in 1815. As well as ash, the eruption released huge amounts of sulfur dioxide gas into the atmosphere. As a result, global temperatures were reduced by about 0.5ºC and the effects of this included:

- changes to the Indian monsoons causing three failed harvests;
- cool temperatures and heavy rains leading to failed harvests across Europe;
- frosts, snow and extensive fog in summer across the farming belt of central USA leading thousands of people to migrate elsewhere;
- cold weather killing trees and rice crops in northern China and flooding of the valley of the river Yangtse;
- painters to paint pictures of beautiful sunsets, caused by ash in the atmosphere;
- a group of authors on holiday in Switzerland to stay indoors and have a contest to write scary stories, leading to the publication of *Frankenstein* and inspiring *Dracula*.

The 1816 famine led to riots and to widespread diseases in different parts of the world.

The high concentration of sulfur dioxide in the 1816 atmosphere was recorded in Greenland ice cores.



1816 temperature fall in Europe

Chichester Canal, a sunset scene, maybe influenced by eruption ash, painted in England by J.M.W. Turner

6.3.1 Resource wars

Many wars have been fought over resources in past times. Sometimes resources are the main factor in the conflict, while they play more minor roles at other times, but they have clearly been key parts of war and peace in the past.

Box 6.15. Water wars

The Middle East region includes the countries of the Arabian Peninsula and the surrounding areas of Egypt, Syria, Iraq, Iran and Turkey. This area is sometimes called the ‘fertile crescent’ because water, particularly from the Nile, Tigris and Euphrates rivers, was used for irrigation and crop-growing, forming the basis of some of the earliest civilisations on Earth, from around 5000 years ago. The long history of this area records many wars, some of them over water supplies. For example, the Assyrian Empire was based on widespread irrigation, and there are records of Assyrian kings destroying the irrigation systems of their enemies or dumping debris into irrigation canals to flood the cities of their foes.

Box 6.15. Water wars, continued

One of the more recent 'water wars' in the Middle East was the conflict over the Jordan River in the mid-1960s. Water from the River Jordan is a vital source of irrigation in Israel. Without it, it might be impossible to support the population. However, the Jordan River rises outside Israel and the surrounding Arab states decided to divert water from the Jordan's headwaters to stop 35% of the water reaching Israel. This was resisted by the Israelis in the Six-Day War of 1967, leading to the plan being abandoned.

The Jordan River, bringing water to Israel from the North

Box 6.16. Oil wars

Many of the wars fought since the 1930s have been described as 'oil wars' because the oil resources of one country were one of the key factors causing the war in the first place.

The first war to be called an 'oil war' was between Bolivia and Paraguay in South America in the mid-1930s. Although won by Paraguay, tens of thousands of soldiers died and both countries were badly affected. In the following years, no commercial amounts of oil were found in the area, although both oil and gas have been found more recently.

The first Gulf war in 1990 was triggered by the invasion of Kuwait by Iraq; disputes between the countries over oil was an important reason for the invasion. The Kuwaiti oilfields were set on fire, greatly damaging them, sending huge plumes of smoke into the atmosphere and causing widespread pollution. It took several months after the end of the war for all the fires to be put out and the oil wells capped.

An important part of the strategy during the second Iraq war that began in 2003 was to secure the Iraqi oilfields; this was completed without damage to the oilfields.

Burning oilfields behind an abandoned tank, Kuwait

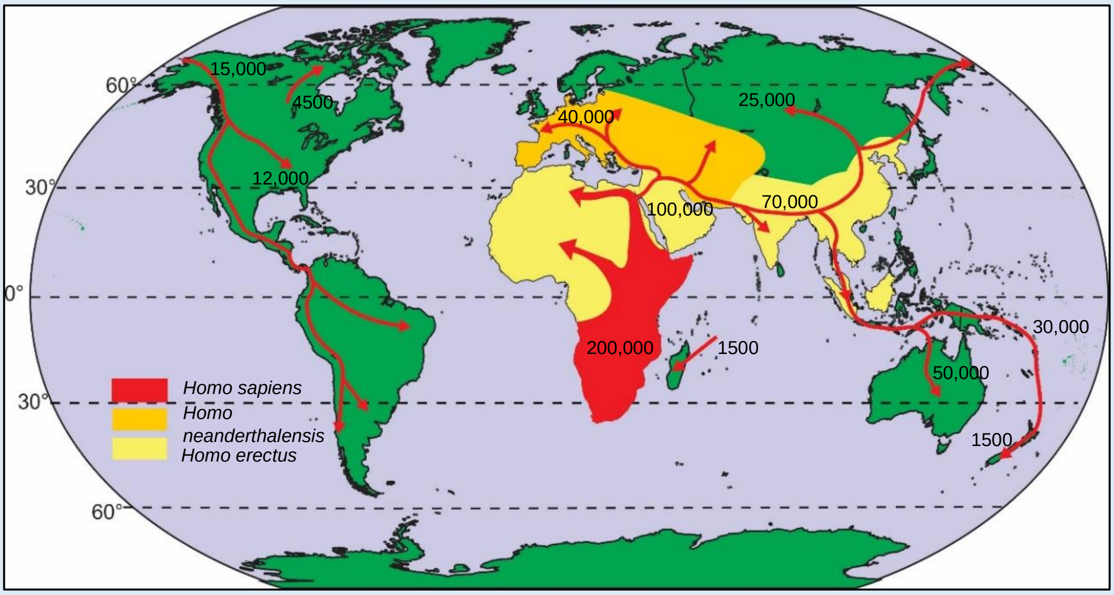
It has been argued that many other conflicts worldwide have oil resources as one of the important contributing factors.

6.3.2 Migration due to climate change

Natural climate change has caused the migration of animals and humans in the geological past because of the changing climate and the linked changes in sea level. Changes in sea level and the movement of climatic belts and of tectonic plates must have caused huge changes of habitats in the geological past, but we have the most detailed evidence of migrations caused in more recent geological times.

Box.6.17. The migration of early humans out of Africa

The migration of early humans and many other groups as well is linked to climate change. The Sahara Pump theory explains that during wetter periods, North Africa and the Middle East became grasslands, allowing many different species to migrate from Africa to Asia. But during drier times, these areas changed back to desert again, as the 'Sahara Pump' stopped. The pump theory has been used to explain waves of migration of several different mammals, including horses, as well as different groups of early humans. The first early human migration from Africa to Asia seems to have happened some 1.75 million years ago. As later human groups evolved in Africa, one of these also migrated along the same route, some 70,000 years ago, to colonise Asia and eventually Europe, the Americas and the rest of the world too.

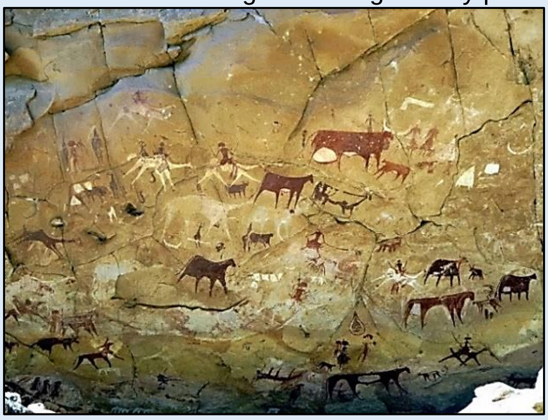


The spread of early human groups across the world, with spreading dates BCE:
first – *Homo erectus*; second – *Homo neanderthalensis*; third – *Homo sapiens*

Box 6.18. The drying of the Sahara

Only around 6000 years ago, the area we now call the Sahara Desert was grassland with a lot of rainfall. The people who lived there then recorded scenes in rock art; these showed many different animals that must have been living in the grassland areas at the time. In the painting site below, camels are painted over other animals and so must have been added later. This may record the beginning of the climate change that left many parts of Chad as one of the driest regions on Earth, with very little water, vegetation or wildlife.

Today the sinking air of the Hadley circulation cell in the atmosphere produces very dry conditions in the Sahara. But the evidence shows that, rainy equatorial conditions can move further away from the equator than they are today. This seems to explain why parts of the Sahara area were so much wetter in the past. Scientists are continuing to investigate why parts of climatic belts might move in this way.



Manda Guéli Cave, Ennedi Mountains, Chad

Wind-eroded rock formation, Ennedi Mountains, Chad

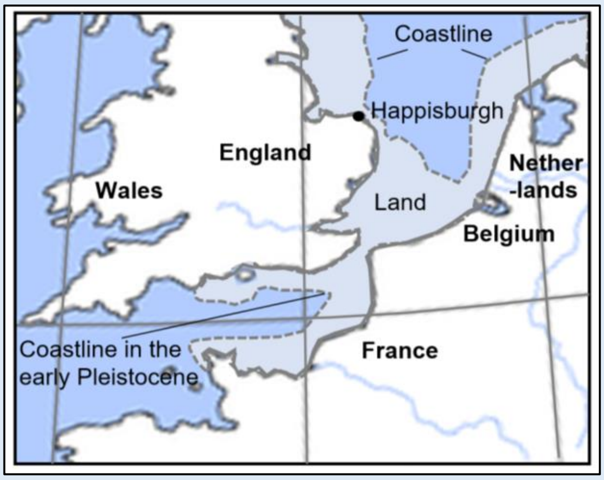
Box 6.3E. When England was connected to Europe – the million-year-old land bridge

Stone tools and footprints have been found in a deposit nearly a million years old in Norfolk. These are thought to have been made by one of the early human ancestors called *Homo antecessor* or 'Pioneer Man'.

At this time, England was part of Europe because in this very cold period, the water locked up in ice sheets meant sea level was much lower than today. This early species of *Homo* walked upright, used tools and lived by hunting and gathering, as we can tell from fossils found in northern Spain. These oldest human fossils in Europe showed that this *Homo* species had a smaller brain, stronger brow ridge, bigger teeth and a flatter face than humans today. The finds in Norfolk show that they were living at the edge of the inhabited world in very cold conditions, and so may have had fire or clothing to help them to survive.

Evidence for these earliest Europeans has been found only in Spain, France and England.

Early human footprints nearly a million years old, Happisburgh, Norfolk



The nearly 1 million-year-old land bridge between England and Europe – caused by low sea levels when global water was locked in ice sheets

Palaeolithic stone tools excavated at Happisburgh, Norfolk

Chris King

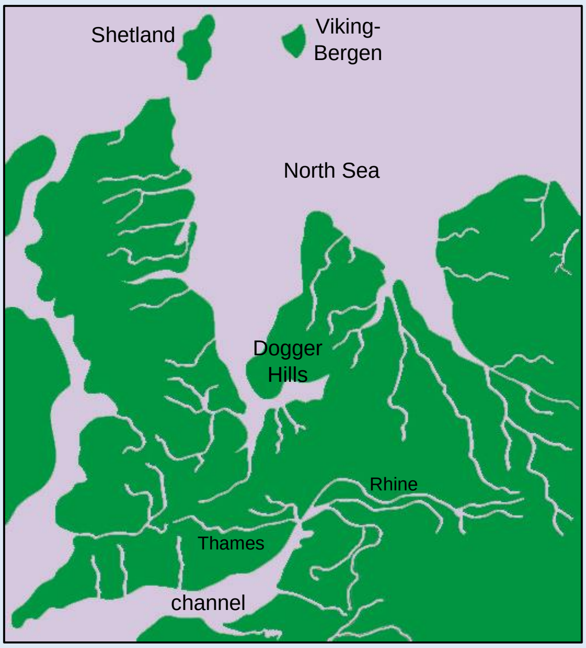
Box 6.19. 'Doggerland' in the North Sea area

Doggerland is the name given to an area, now under the North Sea, that used to be dry land joining the UK to Europe.

The area was a wide shallow valley with low hills and marshlands and rich vegetation and wildlife, inhabited by hunting/gathering bands of humans. This has been shown by the finds of underwater dredges, which dragged up prehistoric tools and weapons, as well as the bones of mammoths, lions and other animals. As the ice caps melted at the end of the last ice age, sea levels rose and gradually flooded the area. A tsunami linked to a sudden underwater slide in the northern North Sea, about 8200 years ago, may have flooded some areas. Rising sea levels seem to have finally drowned Doggerland 6,000 or so years ago.

Box 6.19. 'Doggerland' in the North Sea area, continued

Seismic survey data from oil exploration companies have been used to reconstruct models of what Doggerland looked like in the past, before humans and other wildlife were driven out by rising sea levels. The flooding of Doggerland cut the UK off from the European mainland, making England, Wales and Scotland into an island.



Map of Doggerland around 10,000 BCE

If climate change today results in major changes in sea levels or major movements of climatic belts, we can expect to see more migrations of different types of animals in the future.

7 Earth’s system is explored through fieldwork and practical work

Geoscientists investigate the Earth from atomic to global scales in many different ways. These range from collecting data by observation and measurement during fieldwork to using remote sensing techniques, from modelling geological processes in the lab to modelling them on computer, and from the use of high-tech observation and measuring devices in the laboratory to global monitoring programmes involving the geosphere, atmosphere, hydrosphere and biosphere.

Geoscientists are all those who work on the Earth’s system, and have a wide range of specialisms, some of which are shown in Table 7.1.

Table 7.1. Some of the wide range of geoscience specialisms

Geoscience specialism	Description	Image	Source
Climate scientist	Climate scientists study long-term weather patterns in a region, usually over 30- year cycles; their work ranges from taking water, soil, ice or sediment core samples to using satellite data		Recording glacial data, Glacier National Park, Montana, USA
Engineering geologist	Engineering geologists contribute to major construction projects through geological mapping, leading and interpreting drilling operations, analysing data and preparing recommendations and reports		Charity, an engineering geologist surveying the Cowburn Railway Tunnel at the western end of the Vale of Edale in Derbyshire
Environmental geologist	Environmental geologists monitor the environment during extraction of raw materials or waste disposal, and remediate environments afterwards, using a wide range of data gathered on site and elsewhere		Reviewing an abandoned mining area in the USA
Exploration geologist	Exploration geologists collect data in the field and link it with map, geochemical, geophysical and drilling data in mapping underground rock structures during exploration for oil, gas and mineral deposits		Examining fresh drill core, Chile

Table 7.1. Some of the wide range of geoscience specialisms, continued

Geoscience specialism	Description	Image	Source
Geochemist	Geochemists study the geochemical composition of the Earth from atomic to global scales; geochemistry is used in prospecting for oil, gas and minerals and for monitoring environmental pollution		Studying the geochemistry of volcanic gases, Mount Baker, Washington, USA
Geomorphologist	Geomorphologists investigate how the Earth's surface forms and is changed by Earth processes; they study landscapes linked to weathering, erosion, rivers, coasts and glaciation		Geomorph-ologists measuring sediment transport across the Dee tidal flat estuary off the Wirral in Merseyside
Geophysicist	Geophysicists research earthquakes and carry out seismic hazard assessments; they interpret seismic data collected during exploration for oil, gas and minerals, carry out site investigations, and study the structure of the Earth from surface to core		Vibroseis trucks vibrating the ground to produce shock waves for a seismic profile, operating in the Rivelin valley, Sheffield
Hydrogeologist	Hydrogeologists not only prospect for water and evaluate water prospects but also monitor groundwater for pollution and health risks, take part in the remediation of sites and study mine and quarry dewatering		Sampling groundwater in Germany
Meteorologist	Meteorologists use a wide range of scientific methods to measure, understand, model and predict the weather, its physics and chemistry		Measuring snow depth in Iran

Table 7.1. Some of the wide range of geoscience specialisms, continued

Geoscience specialism	Description	Image	Source
Mine geologist	Mine geologists investigate the links between the geology and ore deposits to follow known ore bodies and find new ones. They advise on short and long-term mining plans through a range of survey methods		Fluorspar vein in a mine, Peak District, England
Oceanographer	Oceanographers include biological, chemical, geological and physical specialisms. Geological oceanographers examine present and past oceanic processes, including plate tectonics, ocean circulation and climate change		The British *RSS James Cook* oceanography research ship loading supplies in Southampton harbour, Hampshire.
Palaeontologist	Palaeontologists study fossils, from microfossils to dinosaurs, studying the evolution of life and the palaeoenvironments where plants and animals once lived; fossils are used to date and correlate rocks and to give information on past temperatures/ climates		Palaeontologist leading a group searching for dinosaur footprints. On the coast near Burniston, Yorkshire
Research geologist	Research geologists usually work at universities, museums or for government departments. University geoscientists lecture to undergraduates, lead doctoral programmes and publish their own research		Louisa, a research geologist in the rock deformation laboratory at the University of Liverpool
Sedimentologist	Sedimentologists study modern sediments and ancient sedimentary rocks to explore their features and to understand the processes that first formed them, working in the field and lab and building physical and computer models		Sediment size analysis in the lab, Naval Oceanographic Office, Mississippi, USA

Table 7.1. Some of the wide range of geoscience specialisms, continued

Geoscience specialism	Description	Image	Source
Soil scientist	Soil scientists classify and map soils, testing their physical, chemical, biological and fertility properties in the field and in the lab; they manage soils for agriculture and remediate soils in environmentally damaged areas		Surveying soil crusts using a quadrat, Tucson, Arizona, USA
Teacher	Teachers teach geoscience to pupils and students from primary (elementary) school level, through secondary (high) school level to university level and beyond, both indoors and outdoors		A teacher discussing fieldwork with a group of school pupils near Ingleton, Yorkshire, UK
Volcanologist	Volcanologists research all igneous processes including those of active volcanoes, studying eruptions, lava flow and release of volcanic gases to work out how they might behave in the future		Testing samples in the crater of Mutnovsky Volcano, Kamchatka, eastern Russia

Geoscientists should follow the Geoethical Promise at all times during their work.

Box 7.1. The Geoethical Promise

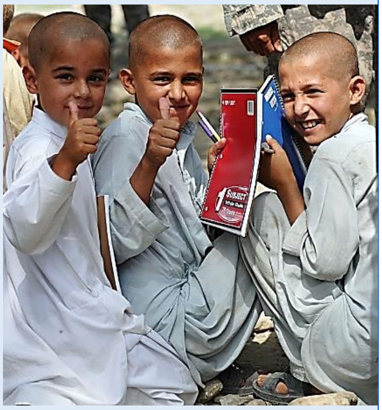
I promise …

- *I will practise geosciences being fully aware of the societal implications, and I will do my best for the protection of the Earth system for the benefit of humankind.*
- *I understand my responsibilities towards society, future generations and the Earth for sustainable development.*
- *I will put the interest of society foremost in my work.*
- *I will never misuse my geoscience knowledge, resisting constraint or coercion.*
- *I will always be ready to provide my professional assistance when needed, and will be impartial in making my expertise available to decision makers.*
- *I will continue lifelong development of my geoscientific knowledge.*
- *I will always maintain intellectual honesty in my work, being aware of the limits of my competencies and skills.*
- *I will act to foster progress in the geosciences, the sharing of geoscientific knowledge, and the dissemination of the geoethical approach.*
- *I will always be fully respectful of Earth processes in my work as a geoscientist.*

I promise!

This important promise should be made by everyone studying geoscience, and can be simplified to:

I promise …



- *I will work in geoscience to best protect the people of Earth and all Earth systems.*
- *I understand that it is my job to help to protect the Earth for the future, through sustainable development.*
- *I will put the interest of all people first in my work.*
- *I will never misuse my geoscience knowledge, whatever other people may say or do.*
- *I will always be ready to use my knowledge of geoscience helpfully, and will try to provide a balanced view to people making decisions.*
- *I will develop my geoscience knowledge throughout my life.*
- *I will always be as honest as I can be.*
- *I will try to move the study of geoscience forward, to share geoscience knowledge, and to help everyone to behave geoethically.*
- *I will always respect Earth processes in my geoscience studies.*

I promise!

Geoscientists in training and during their professional lives use a wide range of skills to observe, measure and monitor the environment, to bring their observations together to explain how environments work today and in the geological past, and to research geological questions and issues.

Fieldwork should only be undertaken when carefully risk-assessed, following health and safety and geological codes of conduct. Details about all these areas are freely available on the internet.

7.1 Observation, measurement and recording

Geoscientific observation, measurement and recording is undertaken at a range of scales, from microscopic to landscape scale and larger. Many of the methods used are shown in Table 7.2.

Table 7.2. Methods used to observe and record the environment, recording geoscientific features

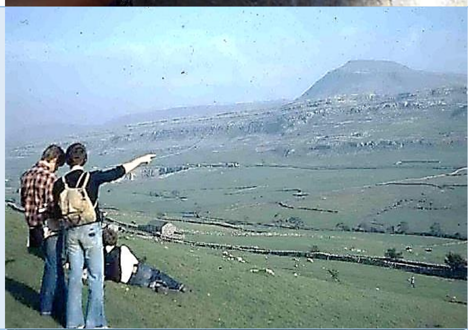
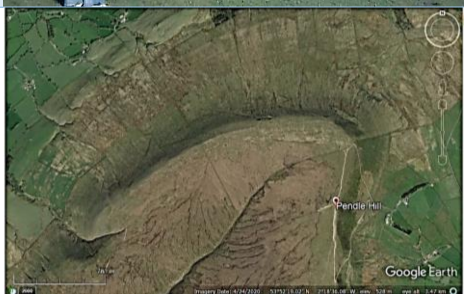
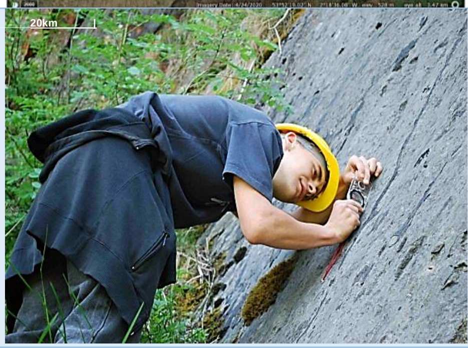
Method	Description	Image	Source
Microscopic observation	Using a single eyepiece or binocular microscope to observe earth materials closely		Observation of microscopic diamonds in Swaziland
Hand lens observation	To use a hand lens in the lab or field, put it close to your eye and bring the material up close to get the best view. This cannot be shown in a camera image, as opposite		Observing a fossil with a hand lens
Landscape observation	Observing landscape as an aid to geological mapping, focussing on breaks and angles of slope and vegetation changes		Landscape observation in the Dales, Yorkshire
Observation using Geographical Information Systems (GIS)	Geological features can be highlighted on GIS, as well as aerial photographs and satellite images		Satellite image of a folded sequence of Carboniferous rocks at Pendle Hill, Lancashire
Field and lab measurement	Measuring dip angle and direction of a sloping bed; dip angle is measured using a clinometer to give the angle of steepest downward slope between 0-90º; dip direction is the direction of greatest downward slope and is a compass bearing from 0-360º		Measuring the dip of a bed in the UK

Table 7.2. Methods used to observe and record the environment, recording geoscientific features, continued

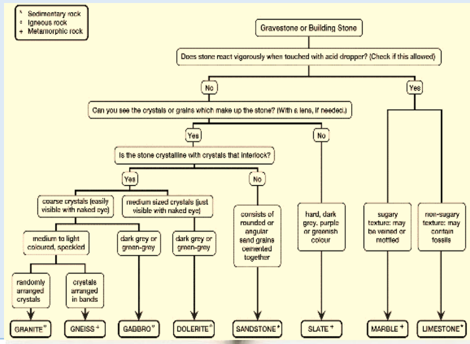
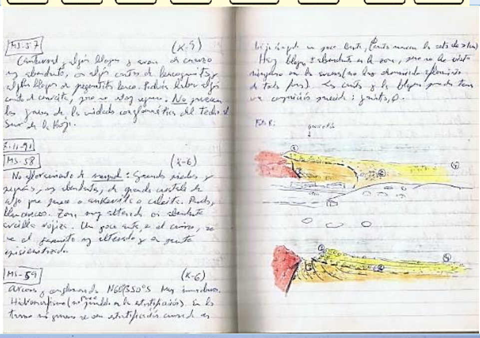
Method	Description	Image	Source
Field and lab measurement, continued	Measurement of differences in thicknesses of beds		Measuring bed thicknesses in the Ecclesall Woods, Sheffield
Field and lab testing	Rocks and minerals can be tested for a range of properties in the lab and field		The streak of hematite samples
Applying classification systems	Classification systems of minerals, rocks, fossils, rock textures, rock structures, rock compositions, etc. can be used, with reference books as a guide		The Earth Science Education Unit rock description key
Recording notes	Notes of geological features are carefully recorded, with details of the date, the localities visited, the features found and their orientations, in notebooks or on tablets		Geology field notes
Recording by diagrams in lab and field	Diagrams are drawn to scale and labelled, and their localities and orientations noted		Recording a field diagram on the metamorphic aureole of the Shap Granite in Cumbria

Table 7.2. Methods used to observe and record the environment, recording geoscientific features, continued

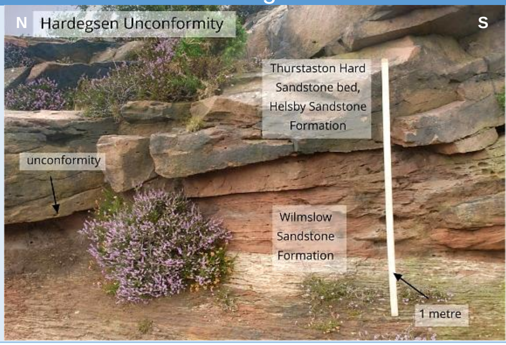
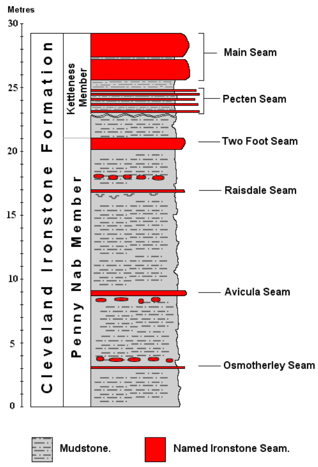
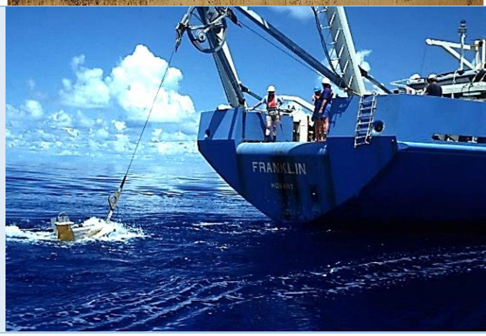
Method	Description	Image	Source
Photographic recording	Photographs make valuable records, particularly when annotated or accompanied by field diagrams		Annotated photograph of the Hardegsen Unconformity at Thurstaston Hill, Wirral, Merseyside
Drawing a graphic log	Graphic or stratigraphic logs are drawn to vertical scale, showing the grain size by the width of the log, and types of sedimentary rock by colour or shading; other features such as sedimentary structures or fossil horizons are added		Stratigraphic log of the Cleveland Ironstone Formation as seen at Staithes in North Yorkshire
Meteorological observation	Regular measurements are made at a Stevenson Screen 		Meteorological station, a Stevenson's Screen to the left, rain gauge and other instruments to the right, in Weston Park, Sheffield, Yorkshire
Air quality sampling	Air quality is monitored, particularly in town and city areas		Air quality sampling in France

Table 7.2. Methods used to observe and record the environment, recording geoscientific features, continued

Method	Description	Image	Source
Digging soil pits	Soil profiles through the horizontal layers in soils are measured by digging pits		Using an auger to extract soil samples, at Ecton in Staffordshire
Water quality sampling	Water is monitored for quality using a range of tests		A Yorkshire Water scientist taking water samples
Oceanographic sampling	Regular measurements are made at sea using a wide range of devices		Sampling the water column in the ocean off Australia

7.2 Synthesis of observations

As field observations are collected they are put together into flexible models of the geological process, history or spatial distribution being studied, as shown in Table 7.3. These pictures build together to help the observer to know what further observations are needed and how best to collect them.

Table 7.3. Building geoscience observations into models and maps

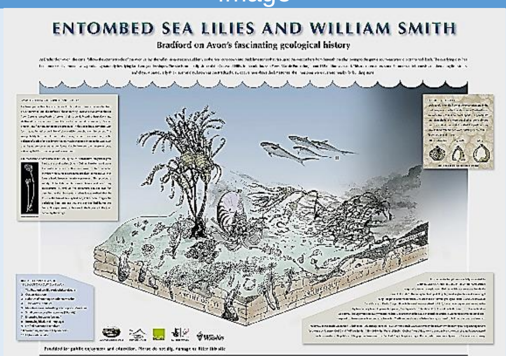
Method	Description	Image	Source
Palaeoenviron-mental interpretation	Geoscientists use the clues they have observed in sedimentary rocks to build a picture of what the area was like when the sediments were laid down		A diorama of Bradford on Avon's fascinating geological history by Alan Bentley

Table 7.3. Building geoscience observations into models and maps, continued

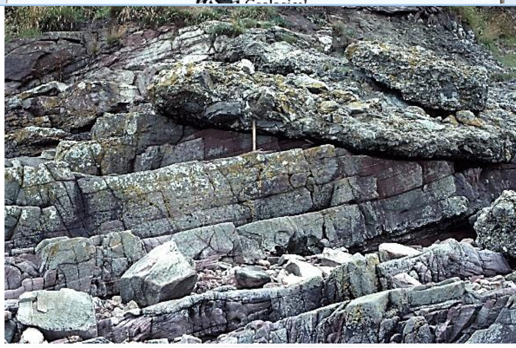
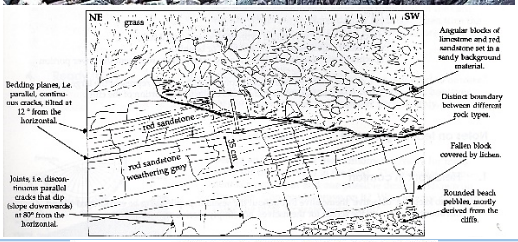
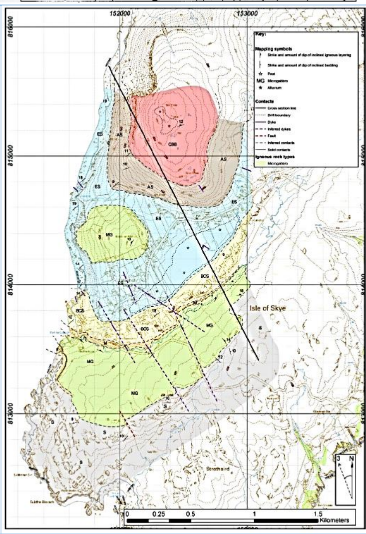
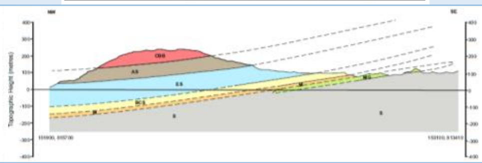
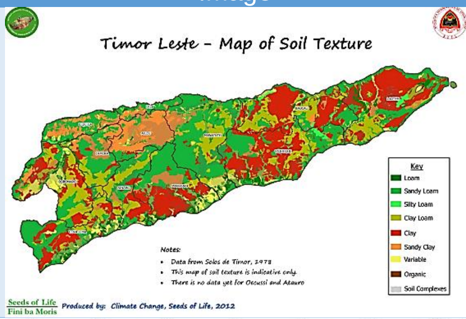
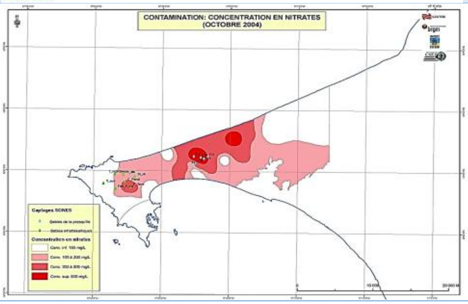
Method	Description	Image	Source
Cooling history of an igneous rock	In igneous rocks with separate large crystals, these crystals began growing earlier in the history of the magma before it intruded into a cooler area and cooled faster, forming a finer-grained mineral background		Large pink feldspar crystals in a finer-grained background igneous rock – showing two-stage cooling. Shap Granite, Shap, Cumbria
Constructing a geological history	Here the lower sediments were laid down, formed into rocks and then tilted by a mountain-building episode; after erosion, the younger rocks were laid down flat on top before being tilted and eroded themselves	 	The unconformity between Devonian rocks below and Triassic rocks above. Portishead coast, Somerset. Annotated sketch below
Drawing a geological map	Surface observations of rock exposures, drainage patterns and changes in slope marking geological boundaries are put together in drawing a geological map – a bird's-eye view of the rocks of the area if all the overlying soil were removed		Geological map of the Strathaird Peninsula, Elgol, Skye, Scotland by Sean Collier
Constructing a geological cross-section	Constructing a cross-section shows the underground geological structure		The cross-section of the Strathaird Peninsula map above

Table 7.3. Building geoscience observations into models and maps, continued

<table>
<tr><th>Method</th><th>Description</th><th>Image</th><th>Source</th></tr>
<tr><td>Drawing a soil map</td><td>Soil scientists map surface soils according to their features; soil maps are used in agricultural planning</td><td>
</td><td>Soil map of the island of Timor</td></tr>
<tr><td>Drawing a map of contamination</td><td>Hydrogeologists map groundwater contamination</td><td>
</td><td>Map of the nitrate contamination of groundwater on the Cap-Vert Peninsula, Senegal</td></tr>
</table>

7.3 Investigation and hypothesis-testing

Geoscientists carry out investigations seeking evidence to answer geoscientific questions.

- First, they are given, or identify for themselves, a question that needs answering or a hypothesis or idea that needs testing.
- The next stage is to put together a plan to investigate the hypothesis or test the idea, that will be flexible enough to be changed during the investigation if early results are not what were expected or give unhelpful information.
- A risk assessment process is carried out and noted.
- Then the plan is carried out, changing and evolving as more information is collected.
- As data are collected, they are processed in different ways, for example by mapping, drawing cross sections, carrying out calculations, plotting data by different means or by building models, including physical models, computer models and mathematical models.
- As the results are collected, they are evaluated to build up an overall picture in response to the original question, to spot unusual information that may or may not be important, and to guide the collection of more data.
- During this process, the results have to be passed on to those needing the information, through a range of methods including reports, presentations and academic publications.

When all this is successful, the results clearly show the outcome of the investigation, answers to the questions have been suggested and hypotheses and ideas have been successfully tested. However, no outcome might be possible due to lack of evidence.

Box 7.2. Geological mapping investigations

In answer to the question "Where do geological formations and the boundaries between them crop out in this area?" a geologist would produce a geological map.

Geological maps are plan views (views from above) of an area showing where the boundaries between geological formations would be seen, if all the soil, buildings and other overlying materials were removed. Geological maps are complex because the boundaries between formations have first to be identified and then their positions must be plotted on topographic maps, considering the relief of the topography. To do this, geologists must know exactly where they are on the topographic map at all times, by measuring bearings, using air or satellite photos or by using Global Positioning Systems (GPS).

A line showing a geological boundary is fairly easy to plot on a map if the difference between the two formations is clear, if the boundary is well exposed and if the boundary is near vertical. Where boundaries are near horizontal, the shape of the boundary is closely controlled by the shape of the ground (the topography) and so can be complex.

Geologists plot maps on topographic base maps in the field. First, they identify the boundary they want to map, then they plot the position of the boundary on their base maps using bearings, photos or GPS systems. They then follow the boundary, dip of the rock and other information, plotting the boundary position as they go. Where the boundary disappears under soil, they use surface features such as changes in slope, vegetation, drainage or changes in soil colour or the rock fragments excavated by burrowing animals, to help them to find the most likely path for the boundary. When the boundary becomes exposed again, they can adjust their 'feature mapping' as necessary. The geological boundaries plotted will include the formation boundaries, faults and the offset of boundaries by faults, and other features such as unconformities or the margins of intrusions; fault movement directions are also recorded.

As geologists are mapping, the dips and dip directions of any bedding planes are recorded and plotted, since these give a guide to the structural history of the sequence – for example, by showing where tilted rocks, anticlines, synclines and faults are found.

Geological boundary between grey sandstone and fine-grained pale granite, Sea Point, Cape Town, South Africa

A major change in slope at the geological boundary between the tough igneous rocks of a sill to the right, and weaker sedimentary rocks to the left, Hadrian's Wall in northern England

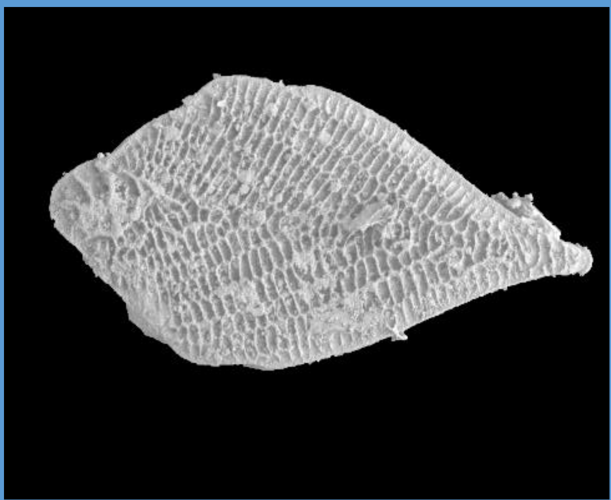
Box 7.1E. The Soham Murders Investigation – a crime solved by geoforensic evidence

On August 4th, 2002, two schoolgirls from Soham in Cambridgeshire disappeared. Thirteen days later their bodies were discovered about 19km from Soham lying in a deep irrigation ditch at Common Drove, a trackway near RAF Lakenheath in Suffolk.

During the crime investigation rocks, sediments, microfossils, and items made from natural earth materials from the Common Drove site and the suspect's car were examined. The forensics team was testing the hypothesis that there was a link between the suspect and the place where the two bodies were found. Materials found at both the Common Drove site and, also on the suspect's car were a mixture of quartz, chalk, Cretaceous bivalve fragments, brick, concrete, and builder's rubble.

This mixture did not provide enough evidence, but the geoforensic experts then analysed the microfossils found in the chalk samples. These samples were taken from Common Drove, the wheel arches and suspension arm of the suspect's car, the car pedals, the carpet in the car, the vacuum cleaner that had been used to clean the car and also a site on Blackdyke Farm where the chalk used to pave Common Drove had been excavated.

The foraminifera and nannoplankton species identified in these samples of chalk showed that they could only be found together in one unit in the chalk that corresponded to one foraminiferal zone (Zone UKB3) and the nannoplankton subzone (Subzone UC1d). These zones occur in a bed of chalk only 2.5 metres thick. This chalk bed does not naturally occur anywhere in the area investigated, but it was established that Common Drove is the only trackway paved with rock from this chalk bed. This geoforensic evidence proved that the suspect must have driven his car along Common Drove and eventually led to the suspect being sentenced to life imprisonment.



Neoflabellina reticulata (a foraminifera species) from the chalk. Length: 1.2mm. Age: Cretaceous, upper Lower Maastrichtian

A false-colour scanning electron micrograph of the nannoplankton species *Gephyrocapsa oceanica*

Maggie Williams

Box 7.2E. 'Who dunnit?'


THE DAILY CHRONIC 50p

13th September 2008

BODY FOUND IN WEST MIDLANDS

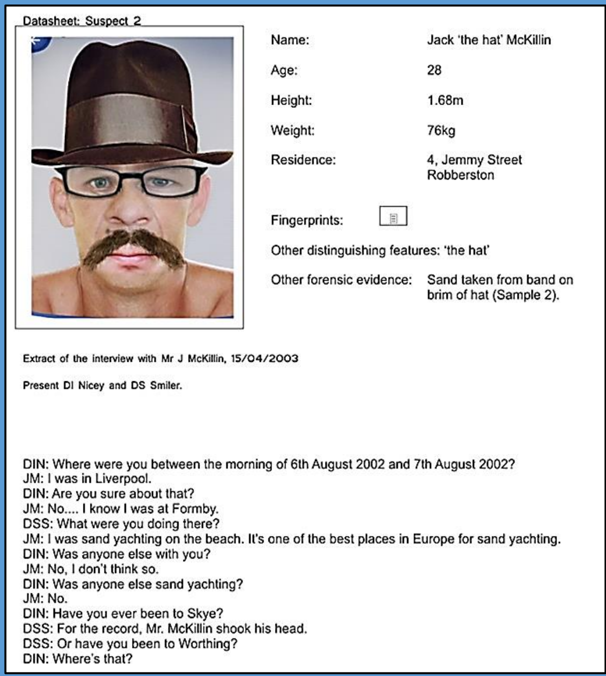
People smuggling four arrested

Early today, a dog walker discovered a body rolled in a blanket near Stourbridge. A Police spokesperson stated that they are treating the death as suspicious and have set up an incident room at the crime scene. They are linking the death to a white van found abandoned near Worthing. They believe that people-smugglers who entered Britain at Staffin on the Isle of Skye dumped the victim when he became ill. Police are asking for anyone who has seen the vehicle to contact their local police station.

White van found abandoned near Worthing.

Detective Inspector Philip Nicey, in charge of investigations said today that they had certain leads that they were following up and that four people had been taken into police custody, three men and one woman, but that nobody had been charged. He said that they were waiting for forensic tests at the crime scene, on the van and on samples taken from the four suspects.

Newspaper report 'setting the scene'


Datasheet: Suspect 2

Name: Jack 'the hat' McKillin

Age: 28

Height: 1.68m

Weight: 76kg

Residence: 4, Jemmy Street Robberston

Fingerprints:

Other distinguishing features: 'the hat'

Other forensic evidence: Sand taken from band on brim of hat (Sample 2).

Extract of the interview with Mr J McKillin, 15/04/2003

Present DI Nicey and DS Smiler.

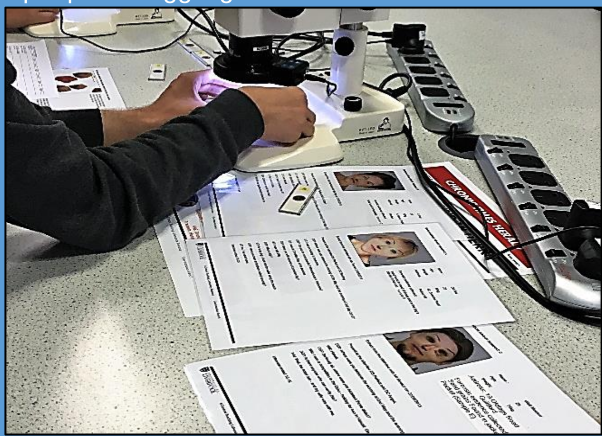
DIN: Where were you between the morning of 6th August 2002 and 7th August 2002?
JM: I was in Liverpool.
DIN: Are you sure about that?
JM: No.... I know I was at Formby.
DSS: What were you doing there?
JM: I was sand yachting on the beach. It's one of the best places in Europe for sand yachting.
DIN: Was anyone else with you?
JM: No, I don't think so.
DIN: Was anyone else sand yachting?
JM: No.
DIN: Have you ever been to Skye?
DSS: For the record, Mr. McKillin shook his head.
DSS: Or have you been to Worthing?
DIN: Where's that?

Example data sheet for one of the four suspects

In this forensics exercise, students carry out an investigation on a range of sand samples, and test the hypothesis that one of four suspects was involved in a people-smuggling crime.

Forensic geoscience uses evidence from geological materials at the scene of a crime to support or defend against a prosecution in court. In this activity students are provided with a newspaper report that 'sets the scene'. Students are also presented with:

- photographs of sand samples taken from the crime scenes,
- photographs of sand samples collected from the four suspects, and
- data sheets for each of the four suspects. These sheets give an outline of interviews with each suspect.



Investigating sand samples

The aim of the activity is for students to investigate the evidence and to draw a conclusion about which of the four suspects is most likely to have been involved with the smuggling crime.

This exercise:

- involves students in active learning and encourages them to develop problem-solving skills
- teaches students that a negative result eliminating someone or something, is still a valuable result
- is adaptable to different age-groups and abilities
- touches on the nature of evidence – what is needed to prove something is true (or false)
- is adaptable to local conditions – local samples of materials (soil or sand or rocks) could be used and /or a local suspect (e.g., the head teacher) could be included
- teaches a social message: criminals need to be caught, but people who look 'bad' are not always guilty and people who have a criminal record might be innocent.

Details of the exercise are available at:
https://geohubliverpool.org.uk/resource/forensic-geoscience-exercise/

Box 7.3. A prospecting investigation for diamonds

Diamonds come from volcanic rocks called kimberlites that are normally found in vertical volcanic pipes, but can also form dykes and sills. Diamonds are rare in kimberlites; much more common are other kimberlitic minerals like garnets, so prospectors seek not diamonds but kimberlitic garnets.

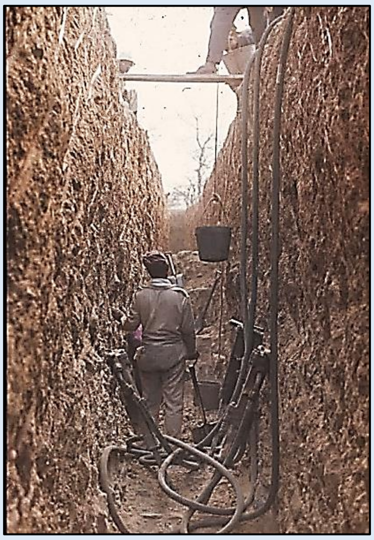
Stream and soil sampling of an area of southern Africa had discovered a narrow north-south trending area of soil about 1km long, rich in kimberlitic minerals, and three microscopic diamonds. The working hypothesis was that these must have come from a north-south trending kimberlite dyke containing diamonds. So a series of east-west trenches was excavated down to the Jurassic bedrock, seeking the dyke – but no dyke was found.

The Jurassic bedrock was largely sandstone, with some mudstone beds, and dipped down towards the west. It was one mudstone bed that was rich in kimberlitic garnets and some diamonds, and its north-south outcrop had produced the garnet-rich soil zone. This was very unusual: never before had ancient sedimentary rocks in Africa been found to contain large amounts of kimberlitic minerals and diamonds.

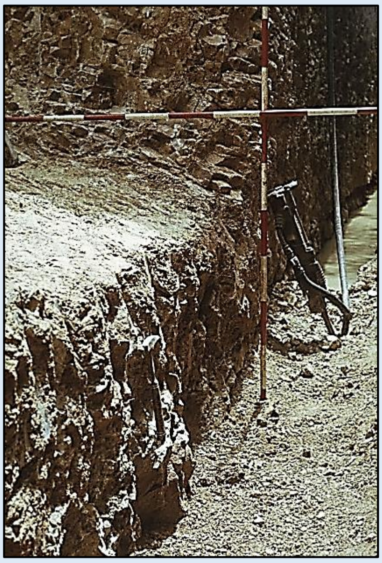
The investigation then needed to move forward in two directions. The deposit had to be tested to discover if it was rich enough in diamonds to be worth mining. Meanwhile prospecting had to continue, to find the original source of the diamonds, hoping that this was mineable too.

Measurements were made on the cross-bedding of the sandstone which showed that the river which deposited the sandstones in Jurassic times had flowed from the west. This was good news because, if the original source of the minerals and diamonds was a kimberlite pipe, it might still be exposed. If the source had been to the east, it would have been buried under more Jurassic sandstones; if it had been to the south or north, it might have been buried too.

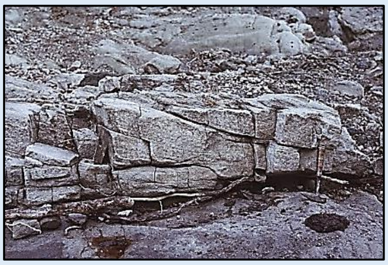
So a further extensive programme of stream and soil sampling was carried out to the west, and eventually a circular area of soil rich in garnets was found. When this was excavated, it was found to be a kimberlite rich enough in diamonds to be mined. The mine worked diamonds successfully for more than fifteen years. Meanwhile, the original deposit was found not to contain enough diamonds to be worth mining at the diamond prices available at the time, although it may still be mined in the future.



Excavating trenches to bedrock (before modern health and safety regulations)



A diamond-rich mudstone layer



Cross-bedded Jurassic sandstone, showing flow of the ancient river from the west (left)

Glossary

Each of these terms is shown in **bold** at or near where it first appears and then is defined in the text. Please use your 'finder' to find the first use of the term, and its definition there.

Absolute dating
Accretionary prism
Aggregate
Albedo
Anticline
Aquifer
Artesian water
Asteroid
Atmosphere

Baked margin
Batholith
Bed
Big bang (theory)
Biosphere
Body fossil

Carbon capture
Cementation
Closed system
Comet
Compaction
Condensation
Confined aquifer
Conservative plate margins
Continental Drift theory
Convergent margins
Correlation

Divergent plate margins
Dyke

Enhanced greenhouse effect
Epicentre
Erosion
Evaporation
Extrusive igneous rock

Fault
Fault plane
Feedback
Flowing well
Focus
Fold
Fold hinge
Fold limb
Fossil

Geosphere
Greenhouse condition
Greenhouse effect
Groundwater

Half-life
Hazards
High pressure
Hydrosphere

Icehouse condition
Igneous rock
Impermeable
Infiltration
Intrusive igneous rock
Island arc
Isoclinal fold

Joint

Lamination
Landslide
Landslip
Leachate
Lithification
Lithosphere
Low pressure
Lunar eclipse

Magma
Magma chamber
Mantle convection mechanism
Mass extinction
Metamorphic aureole
Metamorphic rocks
Metamorphism
Mineral
Mitigation
Mountain roots

Natural hazards (see hazards)
Natural selection
Neap tide
Nebular hypothesis
Negative feedback
Normal fault
Normal magnetic polarity

Open fold
Open system

Partial melting
Permafrost
Permeability
Plate tectonic theory
Pluton
Plutonic rock
Pollutant
Porosity
Positive feedback
Process
Product

Radioactive decay curve
Radiometric dating
Regional metamorphism
Relative dating
Remediation
Renewable energy
Residence time
Reversed magnetic polarity
Reverse fault
Ridge-push mechanism
Rock

Saturated zone
Sea floor spreading theory
Sedimentary rock
Seismic waves
Seismometer
Short carbon cycle
Sill
Slab-pull mechanism
Slushball Earth
Snowball Earth
Soil
Solar eclipse
Spring
Spring tide
Strike-slip fault
Subduction
Supercontinent cycle
Sustainable development
Syncline
System

Thermal metamorphism
Thrust fault
Tight fold
Tipping point
Trace fossil
Transform faults
Transpiration

Volcanic pipe
Volcanic plug
Volcanic rock

Water cycle
Water table
Weathering
Well
Wilson cycle (or J. Tuzo Wilson cycle)

Glossary of elements, compounds and ions

Elements	Compounds	Ions
Al – aluminium	CaO – calcium oxide, lime	Cl^- – chlorine ion
Au – gold	$Ca(OH)_2$ – calcium hydroxide, lime	HCO_3^- – hydrogen carbonate ion
Ca – calcium	$CaCO_3$ – calcium carbonate, calcite	K^+ – potassium ion
Cl – chlorine	$CaSO_4.\ 2H_2O$ – calcium sulfate, gypsum	Mg^{2+} – magnesium ion
Fe – iron	CH_4 – methane gas	Na^+ – sodium ion
H – hydrogen	CO_2 – carbon dioxide gas	SO_4^{2-} – sulfate ion
K – potassium	$CuFeS_2$ – copper iron pyrites, chalcopyrite	
Mg – magnesium	Fe_2O_3 – iron oxide, hematite	
Na – sodium	FeS_2 – iron sulfide, pyrite	
O – oxygen	KCl – potassium chloride, potash	
Pb – lead	NaCl – sodium chloride, halite	
S – sulfur	PbS – lead sulfide, galena	
	SiO_2 – silicon dioxide, quartz	

Appendix

International Geoscience Syllabus, to be encountered by all pupils by the age of 16

Prepared as an internal report on behalf of the International Geoscience Education Organisation (IGEO) and the International Union of Geological Sciences Commission on Geoscience Education (IUGS-COGE) by:

Chris King – United Kingdom

With key contributions from:

Ian Clark – Australia
Rosely Imbernon – Brazil
Luis Marques – Portugal
Ian McKay – South Africa
Bronte Nichols – Australia
Glenn Vallender – New Zealand
Clara Vasconcelos – Portugal
Ashvin Wickramasooriya – Sri Lanka
Michael Wysession – United States of America

International Geoscience Syllabus, to be encountered by all pupils by the age of 16

This syllabus has been prepared by the International Geoscience Education Organisation (IGEO) and the International Union of Geological Sciences Commission on Geoscience Education (IUGS-COGE)

The syllabus is based on the following principles:

- it is based on existing curricula around the world since a syllabus based on existing curricula is most likely to be globally accepted – the matrix of coverage by existing syllabuses begins on page 7;
- the structure of the international syllabus is clearly apparent, even though such structure is not readily apparent in many existing curricula;
- the syllabus is concisely presented on just one page, since a concise syllabus is more likely to be acceptable to non-Earth science educators and teachers; more detail is provided through exemplification on the following pages to indicate the extent of coverage, although it is anticipated that detail will vary from country to country;
- the syllabus does not aim to indicate progression.

International Geoscience Syllabus, to be encountered by all pupils by the age of 16 – core syllabus

By the age of 16, pupils should develop an understanding of the following:

Earth as a changing system

• Attributes	open to energy, almost closed to matter, changing over time, within the solar system, comprising geosphere, hydrosphere, atmosphere, biosphere
• Interactions	interaction of geosphere, hydrosphere, atmosphere, biosphere
• Feedback	positive and negative
• Processes and products	water cycle, rock cycle, carbon cycle
• Energy sources	solar, internal

Earth is a system within the solar system, within the universe

• Origins	big bang; accretion from dust; stars; planets
• The Sun	only external energy source; fluctuations
• Rotational effects	day/night, seasons, Moon phases, eclipses

Earth is a system which has changed over time

• Geological time	span, major events, relative and absolute dating methods, rates of processes

Earth's system comprises interacting spheres -

\- **geosphere**

• Earth materials and properties	minerals, fossils, sedimentary, igneous and metamorphic rocks, soil
• Earth processes and preserved characteristics	surface processes, sedimentary, igneous and metamorphic processes, deformation (AW)
• Structure of the Earth and evidence	crust, mantle, core, lithosphere
• Plate tectonics and evidence	unifying theory, plate construction and subduction, characteristics of plate margins, mechanism, rates of movement; evidence

\- **hydrosphere**

• Continental water	location, processes of movement, uses
• Oceanic water	composition, processes of movement

\- **atmosphere**

• Composition	evolution, current composition
• Flow	processes of movement
• Change	greenhouse effect, planetary influences, human influence, impact on sea level

\- **biosphere**

• Evolution	natural selection, fossil evidence, mass-extinction
• Impact on other systems	role of biosphere in Earth systems

Earth's system produces resources

• Raw materials and fossil fuels	naturally concentrated, non-renewable, uses, need careful managing (sustainable development), potentially polluting
• Renewable energy	issues

Human/Earth system interactions

• Natural hazards	human impact, forecasting, mitigation
• Environmental issues	local to global, mitigation
• Impact on human history	resource wars; migration due to climate change

Earth's system is explored through fieldwork and practical work

• Observation	observation, measurement and recording
• Synthesis of observations	interpretation
• Investigation and hypothesis-testing	devising and implementing plans, processing data, drawing conclusions, evaluating results and communicating findings

International Geoscience Syllabus, to be encountered by all pupils by the age of 16 – core syllabus *with exemplification*

By the age of 16, pupils should develop an understanding of the following:		***Exemplification of the core to indicate the extent of coverage (it is anticipated that this will vary from country to country)***
Earth as a changing system		
• Attributes	open to energy, almost closed to matter, changing over time, within the solar system, comprising geosphere, hydrosphere, atmosphere, biosphere	
• Interactions	interaction of geosphere, hydrosphere, atmosphere, biosphere	*lithosphere/hydrosphere interaction causes coastal processes; hydrosphere/atmosphere interaction causes waves and atmospheric warming; atmosphere/biosphere interaction climatically controls vegetation; lithosphere/biosphere interaction affects soil quality; rates vary from fast to slow*
• Feedback	positive and negative	*positive – increasing area of polar ice sheets gives increased reflection of solar energy, gives increased cooling, gives increasing area of polar ice sheets; negative – the more carbon dioxide is released into the atmosphere, the more that is absorbed in the oceans*
• Processes and products	water cycle, rock cycle, carbon cycle	*unique properties of water, evaporation, transpiration, condensation, precipitation; weathering/erosion, sedimentation, metamorphism, melting, igneous activity; photosynthesis, respiration, burial as limestone/fossil fuel, release by burning/weathering*
• Energy sources	solar, internal	*internal energy from radioactivity and energy from Earth's formation*
Earth is a system within the solar system, within the universe		
• Origins	big bang; accretion from dust; stars; planets	
• The Sun	only external energy source; fluctuations	*solar energy driving the water cycle and weather; long term fluctuations of energy from the Sun related to climate change*
• Rotational effects	day/night, seasons, Moon phases, eclipses	
Earth is a system which has changed over time		
• Geological time	span, major events, relative and absolute dating methods, rates of processes	*major events: 4600 million years (Ma) – formation of Earth; 3600Ma – early life; 550Ma – animals with hard parts; 250Ma – major extinction, including trilobites; 65Ma – major extinction, including dinosaurs; 1Ma ice age; dating principles: superposition, cross-cutting relationships, fossil correlation; radiometric dating; processes occur on a frequency-magnitude spectrum from continuous to catastrophic*

Earth's system comprises interacting spheres -

- **geosphere**

• Earth materials and properties	minerals, fossils, sedimentary, igneous and metamorphic rocks, soil	*definitions of: mineral, fossil, rock, sedimentary rock, igneous rock, metamorphic rock, soil; minerals including: quartz, feldspar, mica, garnet, calcite, halite, gypsum, pyrite, galena; fossils including: trilobite, ammonite, dinosaur; fossilisation processes including: burial, replacement, moulds and casts, trace fossils; rock texture, porosity, permeability; sedimentary rocks including: limestone, chalk, conglomerate, sandstone, clay, shale, rock salt; sedimentary features including: layering (bedding), cross bedding, ripple marks; igneous rocks including: granite, basalt, andesite, gabbro, volcanic ash; metamorphic rocks including: slate, schist, gneiss, marble, metaquartzite (quartzite)*
• Earth processes and preserved characteristics	surface processes, sedimentary, igneous and metamorphic processes, deformation (AW)	*weathering (physical/chemical), erosion, transportation, deposition, lithification, metamorphism, intrusion, extrusion, folding, faulting, jointing*
• Structure of the Earth and evidence	crust, mantle, core, lithosphere	*seismic evidence*
• Plate tectonics and evidence	unifying theory, plate construction and subduction, characteristics of plate margins, mechanism, rates of movement; evidence	*constructive, destructive and conservative margins; past and present evidence*

- **hydrosphere**

• Continental water	location, processes of movement, uses	*surface water, groundwater, ice caps/glaciers; infiltration, downhill flow; water resource management*
• Oceanic water	composition, processes of movement	*salinity; surface flow and waves caused by wind; deep flow due to density differences caused by temperature and salinity*

- **atmosphere**

• Composition	evolution, current composition	*outgassing by early volcanic activity; nitrogen, oxygen, trace gasses including water vapour and carbon dioxide*
• Flow	processes of movement	*unequal heating of Earth, flow due to density differences caused by temperature, oceanic heat source*
• Change	greenhouse effect, planetary influences, human influence, impact on sea level	*temperature graphs over different time spans; link between temperature change and sea level*

- **biosphere**		
• Evolution	natural selection, fossil evidence, mass-extinction	*palaeogeographical effects on evolution; mass-extinction by volcanic activity and impact*
• Impact on other systems	role of biosphere in Earth systems	*biological weathering; biological deposition*
Earth's system produces resources		
• Raw materials and fossil fuels	naturally concentrated, non-renewable, uses, need careful managing (sustainable development), potentially polluting	*oil/gas; metal ores; bulk raw materials; local examples of mining/quarrying*
• Renewable energy	issues	*low pollution, cost, regularity of supply*
Human/Earth's system interactions		
• Natural hazards	human impact, forecasting, mitigation	*eruption; earthquake; tsunami; landslide*
• Environmental issues	local to global, mitigation	*global human impact (causing erosion, pollution, drainage-changes mining/quarrying); burning fossil fuels and greenhouse effect*
• Impact on human history	resource wars; migration due to climate change	
Earth's system is explored through fieldwork and practical work		
• Observation	observation, measurement and recording	
• Synthesis of observations	interpretation	*environment of rock-formation; geological history; environmental issues*
• Investigation and hypothesis-testing	devising and implementing plans, processing data, drawing conclusions, evaluating results and communicating findings	

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NASA	National Aeronautics and Space Administration
USGS	United States Geological Survey
USNOAA	United States National Oceanic and Atmospheric Administration

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Figures

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Figure 4.1. Porosity and permeability in rocks.

Figure 4.2. Argentinosaurus from Argentina, the largest type of dinosaur known so far, and scanning electron microscope images of tiny marine microfossils

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Figure 4.5. The cooling and crystallisation of igneous rocks

Figure 4.6. Igneous bodies in oceans

Figure 4.7. Igneous bodies on continents

Figure 4.8. Thermal metamorphic effects

Figure 4.9. Cross section of the Earth

Figure 4.10. The geology of the Earth's crust. Published by USGS and ipd because it only contains materials that originally came from USGS

Figure 4.11. The most common rocks of the continental crust

- Granite. ESEU. Photo: Peter Kennett
- Gneiss. ESEU. As above
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Figure 4.12. The outer part of the Earth

Figure 4.13. The Pacific Ocean floor; oceanic ridge near the centre and trenches to East and West. Published by http://www.ngdc.noaa.gov/mgg/image/2minrelief.html and ipd

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Figure 4.19. The rift valley at the centre of an oceanic ridge

Figure 4.20. A small rift valley in Iceland, linked to the oceanic ridge rifting. Bridge between continents in Reykjanes peninsula, south-west Iceland across the Alfagja rift valley, the boundary of the Eurasian and North American continental tectonic plates. Published by Chris 73 under CCA-SA 3.0 Unported licence

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Figure 4.34. Plate movement mechanisms

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Figure 4.37. Well-testing

Figure 4.38. A plume of groundwater pollution. Redrawn from http://pbisotopes.ess.sunysb.edu/classes/geo101-notes-07/ex-2-5.htm

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Figure 4.43. Warm red-coloured current flowing over the surface; cold blue-coloured current flowing over the bottom. Photos: Chris King

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Figure 4.45. Generalised surface wind pattern on Earth. Based on redrawing of https://en.wikipedia.org/wiki/Atmospheric_circulation#/media/File:AtmosphCirc2.png

Figure 4.46. Surface ocean circulations. Based on redrawing of https://upload.wikimedia.org/wikipedia/commons/9/9b/Corrientes-oceanicas.png

Figure 4.47. The shallow to deep circulation pattern of the Earth. Based on redrawing of https://en.wikipedia.org/wiki/Thermohaline_circulation#/media/File:Thermohaline_Circulation_2.png

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Figure 4.60. The greenhouse effect

Figure 4.61. The change in carbon dioxide levels in the atmosphere, measured from Moana Loa, Hawaii. Data from Dr Pieter Tans, USNOAA/ESRL and Dr Ralph Keeling, Scripps Institution of Oceanography. Redrawn from an image published by Delorme under CCA-SA 4.0 International licence

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Figure 4.64. Map of continents 85Ma produced through a collaboration between the Earth Science Education Unit and Cambridge Paleomap Services Ltd, who produced the map images used. ESEU gratefully acknowledges the expertise and assistance of Alan Smith and Lawrence Rush of CPSL. Image used with permission of ESEU.

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Figure 5.3. Two slabs of sandstone standing in engine oil – showing how different sandstones can absorb different amounts of oil in their pore-spaces. Peter Craig in King C. (2017) Scottish 'Bring and Share'. From the St Andrews ESTA Conference, September 2016. *Teaching Earth Sciences* 41.2. pp 24-5

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Figure 5.7. The amounts of carbon dioxide released by the burning of different fossil fuels to produce the same amount of energy. Data from the US Energy Information Administration (USEIA) at https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11

Figure 5.8. Recent energy production from different renewable sources. Data from REN21 global status report, Table R1 taken from http://www.ren21.net/wp-content/uploads/2016/10/ REN21_GSR2016_FullReport_en_11.pdf

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………………………………………………………………….

Boxes

Box 1.1. The solar system. Released by Planets2008.jpg under CCA-SA 3.0 Unported licence

Box 1.2. The local water cycle, an example of geosphere, hydrosphere, atmosphere, and biosphere interactions
- Rainfall, May Hill, Gloucestershire. Maggie Williams
- Soil. Published by Ichor202 under GNUFDL
- A spring being caught in a stone trough, Owlcots Lane near Bradford, England. Published by Betty Longbottom as part of the Geograph project collection under CCA-SA 2.0 Generic licence

Box 1.3. Part of the water cycle near your home
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Box 1.4. Sand pattern, Barton on Sea, Hampshire. Published by Clive Perrin as part of the Geograph project and published under CCA-SA 2.0 Generic licence

Box 1.5. View of Poole Harbour. Published by Chris Downer under CCA 2.0 Generic licence

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- Savault Chapel in a clear starry night, in Ouroux-en-Morvan, Bourgogne, France. Published by Benh Lieu Song under CCA-SA 4.0 International licence
- A swirling starscape above La Silla Observatory in Chile. Published by the European Southern Observatory under CCA 4.0 International licence

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- The main asteroid belt. Released ipd by its author, Mdf at English Wikipedia
- Asteroid Gaspra taken from the Galileo spacecraft. Ipd because it was solely created by NASA

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- Hale-Bopp comet in 1997. Published by Philipp Salzgeber under CCA-SA 2.0 Austria licence
- Comet Churyumov–Gerasimenko in September, 2014 as imaged by Rosetta. Published by ESA/Rosetta/NAVCAM, CC BY-SA IGO 3.0 under CCA-SA 3.0 IGO licence

Box 2.4. Planetary geology – Mars
- Geological map of Mars. From http://pubs.usgs.gov/sim/3292/pdf/sim3292_map.pdf. Published by USGS and ipd because it is a work prepared by an officer or employee of the US Government as part of that person's official duties
- The faulted canyon system near the equator. Published by NASA/JPL/USGS and ipd because it only contains materials that originally came from USGS
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- View from the Pathfinder site on Mars. From http://photojournal.jpl.nasa.gov/catalog/PIA02405 and ipd because it was solely created by NASA

Box 2.5. Changing shadows with the time of day
- Photos, Peter Kennett

Box 3.1. Using relative dating methods to work out the geological history of the rocks
- Rock formation in Machtesh Ramon, Israel. Published under the terms of GNUFDL

Box 3.2. An example of a geological period – the Triassic
- The 'golden spike' at the Global boundary Stratotype Section and Point (GSSP) of the Ladinian stage (upper Middle Triassic), Bagolino section, Italian Alps. Published by Xavier Caré under CCA-SA 3.0 Unported licence

Box 3.3. The error range given with radiometric absolute dates
- View of Edinburgh beneath the volcanic rocks of Arthur's Seat in Scotland. Published by Andrew Bell under CCA-SA 3.0 Unported and 2.5, 2.0 and 1.0 Generic licences

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- Cores of deep sea sediments from the deep sea near Greenland. Published by Hannes Grobe under the CCA 3.0 Unported licence
- Grey layer of an 8,000-year-old tsunami deposit, laid down in minutes, with layers of dark peat above and below, from the Storegga tsunami deposit at the Montrose basin, Maryton, Scotland. Published by Stozy10 under the CCA-SA 3.0 Unported licence

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- Stages of impact. Redrawn from: http://www.impact-structures.com/understanding-the-impact-cratering-process-a-simple-approach/

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- Diamond in kimberlite. This image is ipd because it only contains materials that originally came from USGS
- Cut diamonds. Published by Mario Sarto under the terms of GNUFDL, Version 1.2

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- Flint arrowhead. Published by Adrian Michael under GNUFDL
- Chert in limestone. Published by Acar54 and Benzer Fotoğraflar under CCA-SA 4.0 International licence

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- Obsidian specimen, Lake country, Oregon. Published by PAR~commonswiki who released the work ipd
- Obsidian knife. Published by Birmingham Museums Trust, Tom Brindle under CCA-SA 2.0 Generic licence

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- Wormery photos: Peter Kennett, Earthlearningidea

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Box 4.6. Underwater formation of pillow lavas
- A tongue of lava underwater. Published by USNOAA/National Science Foundation and in the public domain because it contains materials that originally came from USNOAA
- Pillows on the sea floor near Hawaii. Published by OAR/National Undersea Research Program (NURP) and ipd because it contains materials that originally came from USNOAA
- Ancient pillow lava, cross-section. Peter Kennett, ESEU

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- Xenoliths of peridotite in volcanic rock, basalt olivine-based xenoliths of iherzolite. Published by Khruner under CCA-SA 4.0 International licence
- Obducted rock, likely to have come from the mantle, chromitic serpentinite from the Kraubath Complex (Speik Complex) in the Eastern Alps of Austria. Published by James St John under CCA 2.0 Generic licence
- Stony meteorite of the NWA 869 meteorite. Published by H. Raab (User:Vesta) under the terms of GNUFDL

Box 4.8. What is the core made of?
- A 1.7 kg individual meteorite from the Sikhote Alin meteorite shower. Published by H. Raab (User:Vesta) under the terms of GNUFDL, Version 1.2

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- Drinking water in a cart. Released by mycurrency.com under CCA-SA 4.0 International license.
- Images of bottled water. Released by saw2th CCA-SA 2.0 Generic license

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- Wind pump near High Thurney Farm, Queniborough, Leicestershire. Alan-Murray-Rust under CC BY-SA 2.0 Unported licence
- Diesel groundwater pump in use today, Staffordshire. John Poyser under CC BY-SA 2.0 Unported licence

Box. 4.13. Ocean currents and the most polluted island on Earth. Words of scientist Jennifer Lavers from http://www.dailymail.co.uk/sciencetech/article-4507612/World-s-polluted-island-revealed.html
- Circulating surface ocean currents in the north and south Pacific Ocean. Ipd because it contains materials that originally came from USNOAA
- The polluted beach of Henderson Island in the south Pacific Ocean. Published by American under the terms of GNUFDL

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- A computer simulation of the ice coverage during ‘Snowball Earth’. Published by Linda Sohl and Mark Chandler at http://www.giss.nasa.gov/research/briefs/sohl_01/ and ipd because it was solely created by NASA

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- Graph of temperature change from the Paleocene to the present. Published by Robert A. Rohde for Global Warming Art under CCA-SA 3.0 Unported license

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- The course of the voyage of the Beagle. Published by Sémhur under CCA-SA 4.0 International generic licence
- Darwin’s finches from the Galapagos Island. Drawn by John Gould and ipd because the copyright term is the author's life plus 100 years or less

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- South-east Asian map published by http://www.ngdc.noaa.gov/mgg/image/2minrelief.html and ipd because it contains materials that originally came from USNOAA

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- *Tyrannosaurus rex*, one of the last dinosaur groups found before the K-Pg mass extinction, Museum of the Rockies. Published by FunkMonk under CCA-SA 2.0 Generic licence
- Collecting ash at the K-Pg boundary. Published by Dcondon under CCA-SA 3.0 Unported licence

Box. 4.20. The Gaia hypothesis of James Lovelock

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- ‘Christmas tree’, North Dakota, USA. Published by Tim Evanson under CCA-SA A 2.0 Generic licence
- Gusher – Lakeview gusher in the USA, around 1911. Published at http://www.sjvgeology.org/history/lakeview/lakeview09.jpg and ipd

Box 5.2. Fracking of shale
- Redrawn from an image by MagentaGreen published under CCA-SA 4.0 International licence

Box 5.3. Seismic prospecting
- A seismic profile, shot across the Eakring oilfield, Nottinghamshire, and its interpretation. Courtesy of the UK Onshore Geophysical Library (UKGOL)

Box 5.4. How to find a diamond mine
- Heavy mineral sampling, jig concentrate and heavy mineral concentrate. Photo: Chris King
- Premier diamond mine, Cullinan, South Africa. Published by Paul Parsons (paul.parsons@hyphen.co.za) under CCA-SA 3.0 Unported licence

Box 5.5. Geothermal energy – is it renewable?
- Experimental hot dry rock geothermal energy plant at Rosemanowas, Cornwall in 1983. John Rostron under CC BY-SA 2.0 Unported licence

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- Lithograph from *The Eruption of Krakatoa, and Subsequent Phenomena*, 1888. Edited by George James Symonds (1838-1900). Published by the Royal Society (UK). Krakatoa Committee, 71-1250, Houghton Library, Harvard University, USA. Ipd because the copyright term is the author's life plus 100 years or less
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Box 6.2. A mega-colossal eruption – Oruanui eruption of the Taupo volcano, around 25,360 years ago
- Artist’s impression of the Oruanui eruption. Published by Anynobody, based on a NASA photograph, published under CCA-SA

Box 6.3. The elastic rebound theory
- Movement of the ground in H.F. Reid’s elastic rebound theory.

Box 6.4. Seismometers
- Seismic recording equipment, Gulf of Corinth, Greece. Photos: Chris King
- Two seismometers, Patras Seismological Laboratory, Greece. Photo: Chris King
- Drum record from a seismometer. Published by Z22 under CCA-SA 3.0 Unported licence

Box. 6.5. The Kobe earthquake, Japan, 1995
- Yasuyo Morita story from http://www.sln.org.uk/geography/7-11kobe.htm
- Damage to a viaduct in Kobe. Released by 野田知明 under CCA-SA 4.0 International licence

Box 6.6. The Kashmir earthquake, Pakistan, 2005 – moment magnitude 7.6
- Mother Shazia Ahmed story. From https://www.oxfam.org.nz/what-we-do/emergencies/previous-emergencies/kashmir-earthquake-2005/stories-from-balakot
- Shazia with her baby who survived for three days in the rubble before being rescued. Oxfam from https://www.oxfam.org.nz/what-we-do/emergencies/previous-emergencies/kashmir-earthquake-2005/stories-from-balakot
- The devastated city of Balakot. Published by the US Air Force and ipd because it is a work prepared by an officer or employee of the US Government

Box 6.7. An earthquake plan
- Earthquake preparedness sign in Vancouver, Canada. Published by Wikiemon under the CCA-SA 3.0 Unported licence
- The Earthquake Country Alliance in California highlights 'Seven Steps to Earthquake Safety'. http://www.earthquakecountry.org/sevensteps/

Box 6.8. 2011 tsunami, Tōhoku, Japan
- Eyewitness account taken from http://factsanddetails.com/japan/cat26/sub161/ item1674.html#chapter-10
- Public hospital in Minamisanriku after the 2011 Tōhoku tsunami, Japan. Published by Christopher Johnson under CCA-SA 2.0 Generic licence

Box 6.9. The Indian Ocean tsunami, 2004
- Interview transcribed from UNISDR video posted on Youtube at https://www.youtube.com/ watch?v=V0s2i7Cc7wA
- Tsunami wave striking the Phuket coast. Published by FlyAkwa under CCA-SA 4.0 International licence

Box 6.10. Tsunami warning information
- Sheet published online by USNOAA Department of Commerce, National Weather Service, Intergovernmental Oceanographic Commission and the International Tsunami Information Center at https://earthweb.ess.washington.edu/tsunami/general/mitigation/mitigation.html

Box 6.11. The Oso mudflow, Spain, 29 March, 2014
- Eyewitness account from https://www.earthmagazine.org/article/oso-landslide-report-yields-some-answers
- The Oso mudslide and its scar. Published by Samantha Ciaramitaro and ipd

Box 6.12. Acid mine drainage
- Acid drainage from an old coal mine, Ecclesall Woods, Sheffield, South Yorkshire. Peter Kennett

Box 6.13. The end of the Minoan civilisation
- Satellite view of the Santorini (Thera) crater today. Published by NASA and ipd

Box 6.14. 'The year without summer', 1816
- 1816 temperature fall in Europe. From http://www.giub.unibe.ch/klimet/docs/luterbacheretal_ science.pdf. Published by Giorgiogp2 under CCA-SA 3.0 Unported licence
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- The Jordan River, bringing water to Israel from the north. Published by Jean Housen under the terms of GNUFDL

Box 6.16. Oil wars
- Burning oil fields behind an abandoned tank, Kuwait, 1991. Published by JO1 Gawlowicz of the US Navy and so ipd

Box 6.17. The migration of early humans out of Africa
- Figure 6.16. The spread of early human groups across the world, with spreading dates: First, Homo erectus; Second, Homo neanderthalensis; Third, Homo sapiens. Redrawn from an image published by NordNordWest and released ipd

Box 6.18. The drying of the Sahara
- Manda Guéli Cave, Ennedi Mountains, north-eastern Chad. Published by David Stanley from Nanaimo, Canada under CCA-SA2.0 Generic licence
- Rock formation, Ennedi Mountains, Chad. Published by David Stanley from Nanaimo, Canada under CCA 2.0 Generic licence

Box 6.19. 'Doggerland' in the North Sea area
- Map of Doggerland. Redrawn from an image published by Max Naylor under CCA-SA 3.0 Unported licence

Box 7.1. The Geoethical Promise. Taken from http://www.geoethics.org/geopromise
- Swearing in at Yuma, Arizona. Published by a US military or Department of Defense employee, taken or made as part of that person's official duties. As a work of the US federal government, the image is ipd
- Afghan children. Published by a US Army soldier or employee, as above

Box 7.2. Geological mapping investigations
- Geological boundary between grey sandstone and fine-grained pale granite, Sea Point contact, Cape Town. Photo: Chris King
- A major change in slope at the geological boundary between tough igneous rocks of a sill to the right and weaker sedimentary rocks to the left. View along the Whin Sill to Crag Lough, from above Milecastle 39 on Hadrian's Wall, northern England. Published by Nilfanion under the CCA-SA 3.0 Unported licence

Box 7.3. A prospecting investigation for diamonds
- Photos: Chris King

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Tables

2.1. Planets of the solar system
- Mercury from the Messenger flyby. Published by NASA and ipd
- Venus from Mariner 10 images. Published by NASA and ipd; image processing by R. Nunes at http://www.astrosurf.com/nunes
- Earth following the BlenderGuru.com tutorial. Published by Jason Harwell under CCA-SA 3.0 Unported licence
- Mars from the Hubble telescope. Published by NASA and ipd
- Jupiter from Voyager 1 images. As above
- Saturn from Voyager 2. As above
- Uranus from Voyager 2. As above
- Neptune from Voyager 2. As above

Table 2.2. The tilt of the Earth causing seasons

Table 3.1. Relative dating methods
- Layers laid down in a glacial lake called varves, Barmston, Yorkshire. Peter Kennett
- Overturned fold, The Lizard, Cornwall. Peter Kennett
- Cross-cutting white mineral veins, Porthmeor, Cornwall. Peter Kennett
- Shap granite including dark rock fragments, Shap, Cumbria. Maggie Williams
- Drawings from William Smith's book of a group of fossils used to date a rock, Lower Chalk in England. Drawings by James Sowerby. Ipd as the copyright term is the author's life plus 70 years or less
- Unconformity in Vallis Vale, Somerset. Alan Holiday

Table 3.2. Principles of the laying down of sediments, lavas and volcanic ash
- Carboniferous sandstones laid down horizontally – Crowden Quarry, Derbyshire. Peter Kennett
- Carboniferous sediments not originally laid down horizontally – cross-bedded sands, Walkley Bank, Sheffield, Yorkshire. Peter Kennett
- Mam Tor, Derbyshire. Released by Rob Bendall for any use
- Buried valley, Bardon Hill Quarry, Leicestershire, Pete Loader

Table 3.3. William Smith's method applying the 'Law of faunal succession'
All James Sowerby's fossil drawings in William Smith's publications are ipd since the copyright term is the author's life plus 70 years or less

Table 3.4. Typical fossils found in rocks of different ages

- Argopecten gibbous scallop. Published by FWC Fish and Wildlife Research Institute under CCA 2.0 Generic licence
- Gastropod from the Red Crag in Norfolk. Peter Kennett
- Shark tooth. Peter Kennett
- Micraster echinoderm. Peter Kennett
- Jurassic ammonite. Elizabeth Devon
- Ceratites ceratite ammonoid. Published by BerndH under CCA-SA 3.0 Unported licence
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- Monograptus. Elizabeth Devon
- Didymograptus. Elizabeth Devon
- Paradoxides. Published by Sam Gon III for use for any purpose

Table 3.5. The main subdivisions of geological time

Table 4.1. Common minerals, their chemistry, shape and physical properties
- Quartz with pyrite. British Geological Survey P693083
- Feldspar crystal from the Roneval veins, Lewis, Outer Hebrides. British Geological Survey P527643
- Mica crystal from Loch Nevis Mica Prospect, Knoydart, Inverness. British Geological Survey P527652
- Calcite from Egremont. Rob Lavinsky, iRocks.com – CC-BY-SA-3.0
- Halite. Maggie Williams
- Gypsum from Jurassic clay near Weymouth. Peter Kennett
- Pyrite from West wheal Kitty. Published by AnemoneProjectors under CCA 2.0 Generic licence
- Galena Wanlockhead Lead Mine, Dumfries, Scotland. British Geological Survey, P528051

Table 4.3. Important processes of fossilisation
- Fossil mammal showing fur – the Eomaia scansoria fossil displayed in Hong Kong Science Museum, China. Published by Laikayiu under GNUFDL
- Cotswold *Gryphaea*. Peter Kennett
- Ammonite. Elizabeth Devon
- Internal and external moulds of gastropods in Portland stone. Peter Kennett
- Dinosaur footprint cast, Fairlight, Sussex. Published by Sandpiper under CC0 1.0 Universal Public Domain Dedication
- Burrows in Carboniferous mudstone, Cocklawburn beach, Northumberland. Elizabeth Devon
- Rootlet traces – probably of reed or marsh plants, Saint Hill near East Grinstead. British Geological Survey, P210124

Table 4.5. Common sedimentary rocks
- Conglomerate specimen. ESEU. Peter Kennett
- Conglomerate outcrop. Graham Cole under CCA 2.0 Generic licence
- Buff-coloured sandstone specimen. ESEU
- Cross-bedded buff-coloured sandstone, on Burbage Edge near Sheffield, Yorkshire. Peter Kennett
- Red sandstone specimen. ESEU. Peter Kennett
- Cross-bedded red sandstone near Dawlish, Devon. N. Chadwick under CCA 2.0 Generic licence
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- Mudstone in a former brick pit, Sheffield, Yorkshire. Peter Kennett
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- Fossiliferous limestone. ESEU. Photo: Peter Kennett
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- Rock salt in Boulby Mine, North Yorkshire. British Geological Survey, P222284
- Coal specimen. ESEU. Peter Kennett
- Blindwells Opencast Coal site, Tranent, East Lothian. British Geological Survey, P001520

Table 4.7. Common igneous rocks
Specimen images
- Granite. B. Domangue under CCA-SA 4.0 Unported licence
- Granite exposure, tor on Dartmoor of the Dartmoor granite, intruded around 280Ma during the Permian period. Maggie Williams
- Gabbro. ESEU. Peter Kennett
- The Carrock Fell gabbro, intruded around 450Ma during Ordovician times. Carrock Fell, Cumbria. David Purchase under CCA-SA 2.0 Unported licence
- Dolerite. Collection of National Museum, Prague, Czech Republic. Published by Karelj and released ipd
- The 300Ma dolerite Whin Sill intrusion is used as a defensive position by Bamburgh Castle in Northumberland. Pete Loader
- Basalt. ESEU. Peter Kennett
- Exposures of Carboniferous polygonal basalt columns in Borthwick Quarry, Duns, Scottish Border near Berwick-upon-Tweed. Elizabeth Devon
- Andesite. Published by Michael C. Rygel under CCA-SA 3.0 Unported licence
- Andesite lava of Ordovician age exposed at Jopplety How, Borrowdale, Cumbria. Peter Kennett
- Volcanic ash. Source: http://resourcescommittee.house.gov/subcommittees/emr/usgsweb/ photogallery/; English Wikipedia, original upload 3 August 2004 by Chris 73. As a work of the US federal government, the image is ipd
- Layers of Carboniferous volcanic ash above an explosive deposit of volcanic blocks and ash, Weston-super-Mare, Somerset. Peter Kennett

Table 4.9. Common metamorphic rocks
Specimen images
- Slate. ESEU. Peter Kennett
- Borrowdale Slates, Dunnerdale, Cumbria. British Geological Survey, P005162
- Schist. ESEU. Peter Kennett
- Hornblende schists forming the cliffs at Lizard Point, Cornwall Probably Cambrian in age. Chris Downer under CCA-SA 2.0 Unported licence
- Gneiss. ESEU. Peter Kennett
- Banded gneiss exposed on Kennack Sands, The Lizard, Cornwall. Anne Burgess under CCA-SA 2.0 Unported licence
- Marble. ESEU. Peter Kennett
- Marble block, Carrara quarry, Italy. Published by Lucarelli under GNUFDL
- Metaquartzite (quartzite). ESEU. Peter Kennett
- Metaquartzite. Breakwater Country Park, near Holyhead, Anglesey. Maggie Williams

Table 4.10. Common weathering processes
- Freeze-thaw fracturing in a limestone block on a wall, Grindleford, Derbyshire. Peter Kennett
- Sheets of granite breaking away due to heating/cooling, Half Dome, Yosemite National Park, USA. Published by HylgeriaK under CCA-SA 3.0 Unported licence
- Carboniferous limestone pavement with widened joints (grykes), Austwick, North Yorkshire. Peter Kennett
- Oxidation weathering to a surface rusty colour. Carboniferous mudstones, Neepsend Brickpit, Sheffield, Yorkshire. Peter Kennett
- Lichens growing on a sandstone gatepost, Sheffield, Yorkshire. Peter Kennett
  Soil profile on a cliff, Gower, Wales. Peter Kennett

Table 4.11. Important erosional processes
- Bank collapse due to undercutting by erosion of the Skell River near Ripon, Yorkshire. Stephen Craven under CC BY-SA 2.0 Unported licence
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- Dust storm over a newly ploughed field, Rufford, Nottinghamshire. Jonathan Thacker under CC BY-SA 2.0 Unported licence
- A wind-eroded rock at Bridestones on the North York Moors, Yorkshire. Julia Kay
- Bedrock scratched by a glacier carrying rock debris, Austwick, North Yorkshire. Peter Kennett

Table 4.12. Landforms formed by resistant rock layers
- Ingleborough plateau from Simon Fell, North Yorkshire. Mick Melvin under CC BY-SA 2.0 Unported licence
- Stanage Edge cuesta from Burbage Derbyshire. Peter Kennett
- The East Ridge of Bannerdale Crags, near Scales, Cumbria. Karl and Ali under CC BY-SA 2.0 Unported licence
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- Coastal cliff and stack, Sidmouth, Devon. Peter Kennett
- Slumping coastal cliffs, Shippards Chine, Isle of Wight. Published by Graham Horn under CCA-SA 2.0 Generic licence

Table 4.13. Landscape features formed mainly by erosion and deposition
- V-shaped Carding Mill Valley, Long Mynd, Shropshire. Brian Smithson under CC BY-SA 2.0 licence
- U-shaped glacial valley on the River Swale in North Yorkshire. Christine Johnson under the CC BY-SA 2.0 Unported licence
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- River Derwent delta building out into Derwent Water, Cumbria. Rose and Trev Clough under CC BY-SA 2.0 Unported licence
- Glacial moraine making hummocky ground in Deepdale U-shaped valley near Hartsop, Cumbria. Michael Graham under CC BY-SA 2.0 Unported licence

Table 4.14. Important sedimentary structures
- Horizontally bedded Carboniferous limestones of different thicknesses, Cullernose Point, Northumberland. Pete Loader
- Laminated mudstone either side of an uneven sandstone bed in the Carboniferous Bowland Shales, Collyholme Wood, Lancashire. British Geological Survey, P005733
- Large-scale (wind-formed) cross-bedded Permian sandstone, Dawlish, Devon. Tony Atkin under CC BY-SA 2.0 Unported licence
- Asymmetrical ripple marks in Carboniferous sandstone, Brincliffe Edge, Sheffield. Peter Kennett
- Symmetrical ripple marks in Cretaceous sandstone near Partridge Green, West Sussex. British Geological Survey, P212415
- Graded bedding – Eocene grit in a garden wall near Besalú in Catalonia, Spain. Photo: Pete Loader
- Desiccation cracks formed by sand filling mudcracks in the bed below, Jurassic sandstone, Whitby, Yorkshire. Peter Kennett

Table 4.15. Important igneous features
- Modern pillow lavas on the ocean floor, taken during the Galapagos Rift Expedition in the west Pacific Ocean, 2002. Published by USNOAA Photo Library: on Flickr: expl1528 under the CCA 2.0 Generic licence
- Pillow lavas compressed in a mountain building episode Devonian age rocks, Gunards Head, Cornwall Ashley Dace under the CC BY-SA 2.0 Unported licence
- The Whin Sill at High Cup Nick in Cumbria. The dark-coloured sill has intruded flat-lying Carboniferous limestone. Marathon under CC BY-SA 2.0 Unported licence
- Pale granite dyke cutting through darker bedrock at Porthmeor in Cornwall. Peter Kennett
- Satellite image of the Bodmin Moor granite pluton in Cornwall. From the Geology of Britain Viewer on the BGS website at: http://mapapps.bgs.ac.uk/geologyofbritain/home.html

Table 4.16. Metamorphic rocks formed by regional metamorphism
- Mudstone. ESEU. Photo: Peter Kennett

- Slate. As above
- Schist. As above
- Gneiss. As above
- Granite. As above
- Sandstone. As above
- Metaquartzite (quartzite). As above
- Fossiliferous limestone. As above
- Marble. Published by Beatrice Murch under CCA 2.0 Generic licence

Table 4.17. Fractures caused by brittle failure – joints and faults
- Two sets of vertical joints cutting horizontal bedding in Jurassic limestone; Saltwick Nab near Whitby, North Yorkshire. Stephen McCulloch under the CC BY-SA 2.0 Unported licence
- Normal fault of a coal seam in Carboniferous Coal Measures, Skelmersdale, Lancashire. Peter Kennett
- View from above of the Piquiang Fault, Tein Shan Mountains, China. Published by NASA Earth Observatory images by Robert Simmon and Jesse Allen, and ipd as it was created by NASA
- Reverse fault in volcanic ash, Borrowdale in Cumbria. Peter Kennett
- Thrust fault, Lilstock Bay, Somerset. Mikenorton under CCA-SA International licence

Table 4.18. Fold types
- An anticline in Carboniferous limestone, Apes Tor, Staffordshire. Peter Kennett
- A syncline in Carboniferous limestone, Apes Tor, Staffordshire. British Geological Survey, P006280
- An open fold in Carboniferous limestone beneath the Whin Sill, Swine Den Northumberland. Jonathan Wilkins under CC BY-SA 2.0 Unported licence
- Tight folds with almost angular hinges in well-bedded Carboniferous limestone in the Clayton Mine, Ecton, Staffordshire. Peter Kennett
- Tight fold with rounded hinge in a thin dark limestone bed within black shale bands between pale Carboniferous limestone beds in the Clayton Mine, Ecton, Staffordshire. Peter Kennett
- An isoclinal fold dipping down towards the left in Carboniferous sandstone, Hartland quay, Devon. Peter Kennett

Table 4.19. Oceanic crustal rocks
- Sediment core from South Atlantic. Published by Hannes Grobe/AWI under CCA Unported licence
- Gabbro. ESEU, photo: Peter Kennett
- Dolerite. Published by Karelj and released ipd
- Basalt. As above

Table 4.20. Characteristics of the Earth layers

Table 4.21. Processes of the internal rock cycle now explained by plate tectonic theory

Table 4.22. The main evidence supporting plate tectonic theory
- Jigsaw shape – the Continental jigsaw, continental shelf. © Andrew McLeish in *Geological Science*, redrawn by ESEU and used with permission
- Geological evidence on 'the jigsaw' – distribution of ancient rocks across South America and Africa. © Andrew McLeish in *Geological Science*, redrawn by ESEU and used with permission
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- Palaeoclimatic evidence – the Continental jigsaws (former distribution of ice across the Gondwana continents). © Andrew McLeish in *Geological Science*, redrawn by ESEU and used with permission
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- Age of the ocean floor. Published by USNOAA and ipd because it contains materials that originally came from USNOAA
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Table 4.23. Continental water on Earth
Percentage data from http://water.usgs.gov/edu/earthhowmuch.html. Source: Igor Shiklomanov's chapter 'World Fresh Water Resources' in Peter H. Gleick (editor), 1993, *Water in Crisis: A Guide to the World's Fresh Water Resources* (Oxford University Press, New York)
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Table 4.24. Coastal features produced by waves and tides
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- Tidal mud flats in the Lower Halstow Creek estuary, Kent. N. Chadwick under CC BY-SA 2.0 Unported licence
- Hurst spit, Hampshire. Oast House Archive under CC BY-SA 2.0 Unported licence

Table 4.25. Problems likely to be caused by a warming Earth

Table 4.26. The contribution of life to rock-formation
- Coal-formation – leaf fossils in Carboniferous coal. From the Natural History Museum Library, London, and ipd since the copyright term is the author's life plus 70 years or less
- *Cladophyllia* reef coral, Middle Jurassic age, Wiltshire. Elizabeth Devon
- Limestone of brachiopod shell fragments. National Stone Centre, Wirksworth, Derbyshire. Peter Kennett
- A scanning electron microscope image of coccoliths. Published by Hannes Grobe/AWI under CCA licence
- Burrows in a boulder of Jurassic limestone, Burniston, Yorkshire coast. Peter Kennett

Table 5.1. Natural resources from the Earth
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- Watergrove Reservoir, Wardle, Rochdale, Greater Manchester. David Dixon under CC BY-SA 2.0 Unported licence
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- Fishing boats, Beer, Devon. David Martin under CC BY-SA 2.0 Unported licence

Table 5.2. Examples of bulk raw materials
- Quarrying Precambrian igneous rock at Bardon Hill, Leicestershire. Peter Kennett
- Carboniferous limestone quarries, Buxton, Derbyshire. Richard Bird under CC BY-SA 2.0 Unported licence
- Sand and gravel pit in the Thames Valley, Thorpe, Surrey. Peter Kennett

Table 5.3. Examples of bulk raw materials used in making building materials, and the ceramic and chemical industries
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- Hardendale modern lime kilns, Shap Fell, Cumbria. Alan Murray-Rust under CC BY-SA 2.0 Unported licence
- Historical image of Witton Hall Rock Salt mine, Northwich, Cheshire. P232463, British Geological Survey
- The surface workings of the Boulby deep potash mine in North Yorkshire. Mick Garrett under CC BY-SA 2.0 Unported licence
- A gypsum quarry in Triassic rocks near Nottingham, England. Published by Jim Thornton as part of the Geograph project under CCA-SA 2.0 Generic licence
- Brick clay in the old Neepsend Brickworks quarry in South Yorkshire; Carboniferous age. Peter Kennett
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- Silica sand quarry near Kennythorpe, North Yorkshire. Gordon Hatton under CC BY-SA 2.0 Unported licence

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Table 5.5. Examples of industrial mineral extraction
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- The Mir mine, Mirny, Russia. Published by Staselnik under the CCA-SA 3.0 Unported licence

Table 5.6. The five requirements to form an oil and/or gas field
- An anticline in Carboniferous sandstone, Upton, near Bude in Cornwall. Derek Harper under CC BY-SA 2.0 Unported licence
- Fine-grained Carboniferous shale, Rotherham, South Yorkshire. Peter Kennett
- Sandstone naturally containing oil, from the Hutton oil field in the North Sea. Peter Craig in King C. (2017) Scottish 'Bring and Share', from the St Andrews ESTA Conference, September 2016, *Teaching Earth Sciences',* 41.2. pp 25
- Oil source rock; the Jurassic Kimmeridge Clay below Houns Tout near Worth Maltravers in Dorset. Robin Webster under CC BY-SA 2.0 Unported licence

Table 5.7. Methods of protecting the environment during exploitation of natural resources
- View of a sand and gravel quarry taken from the top of the bund built to hide the site, near Four Oaks, Solihull, Warwickshire. Robin Stott under CC BY-SA 2.0 Unported licence
- Screening by tree-planting near a new bund, on the left and in the background, Avon Common, Hampshire. Mike Faherty under CC BY-SA 2.0 Unported licence
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Table 5.8. Examples of remediation
- The former Haytor granite quarry, now landscaped and turned into a country park in Devon. Janine Forbes under CC BY-SA 2.0 Unported licence
- A reclaimed old brick pit, now filled with landfill, capped and landscaped, Stairfoot, Barnsley, South Yorkshire. Peter Kennett
- The world's oldest preserved mine engine winding house, Ecton Hill, Staffordshire. Peter Kennett
- The Eden Project in Cornwall. Published by Richard Johns for the Geograph project under CCA-SA 2.0 Generic licence
- Student fieldwork at Apes Tor, an old limestone quarry, Staffordshire. Chris King

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- A solar farm near Bentham in North Yorkshire. Ian Taylor under CC BY-SA 2.0 Unported licence
- Blackburn Meadows biomass power station near Rotherham, South Yorkshire. Derek Harper under CC BY-SA 2.0 Unported licence
- The Burbo Bank offshore wind farm on the Burbo Flats in Liverpool Bay, in the Irish Sea. Maggie Williams
- The Southampton geothermal plant. Hugh Venables under CC BY-SA 2.0 Unported licence
- An experimental tidal power plant installed in the estuary of the river Humber to generate electricity for the Hull aquarium in East Yorkshire. Christine Johnstone under CC BY-SA 2.0 Unported licence
- One of the three Pelamis machines bursting through a wave at the Aguçadoura Wave Park, Portugal. Published by P123 and released ipd

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- Lahar burying houses near the Galanggung volcano, Indonesia, 1983. Published by Robin Holcomb, USGS, and ipd because it contains materials that originally came from USGS

Table 6.2. Eruptions according to the Volcanic Explosivity Index (VEI)
- Lava from Puʻu ʻŌʻō volcanic cone Kilauea, Hawaii, USA, 1997. Published by Brian Snelson (exfordy on Flickr) at http://www.flickr.com/people/exfordy/ under the CCA 2.0 Generic licence
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- The huge volcanic crater (caldera) from the three Yellowstone eruptions, Wyoming, USA. Published by Ed Austin/Herb Jones and, ipd as a work of a National Park Service employee of the US federal government

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Table 6.4. The moment magnitude scale

Table 6.5. Some of the most dangerous earthquakes, according to the numbers of deaths

- Earthquake map distribution. Published by NASA and ipd because it was solely created by NASA

Table 6.6. Methods of forecasting earthquakes

- The Loma Prieta gap on the San Andreas Fault, California, USA. Ipd because it only contains materials that originally came from USGS
- Map of Japan. Published by Alexrk2 under CCA-SA 3.0 Unported licence
- Seismic hazard map of South America prepared by USGS. Published by USGS Department of the Interior/USGS and released ipd

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- The 2004 tsunami at Ao Nang, Krabi Province, Thailand. Published by Bild:Davidsvågfoto.JPG and may be used by anyone for any purpose
- The result of the tsunami caused by the 1883 Krakatoan eruption. From the Anales de la Sociedad Espala de Historia Natural, source: https://www.flickr.com/photos/ internetarchivebookimages/18162559072/; ipd as it is more than 100 years old
- An artist's view of the 1755 Lisbon, Portugal, earthquake and tsunami. Ipd as it is more than 100 years old

Table 6.9. Methods used to increase safety during tsunamis

- The tsunami hazard warning leaflet prepared for the coastal city of Pichilemu in central Chile. Published by Gobierno de Chile, ONEMI under CCA 3.0 Chile licence
- A tsunami wall at Tsu-shi in Japan. Published by Rudolf Ammann under CCA 2.0 Generic licence
- The DART II network warning system buoy. This image is ipd because it contains materials that originally came from USNOAA
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Table 6.10. Different types of landslides and flows

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- Terracettes below Morgan's Hill, Wiltshire, England. Derek Harper under CC BY-SA 2.0 Unported licence

Table 6.11. Major landslides
- 1920 Haiyuan earthquake which triggered the Haiyuan flows in central China. Published by User:PhiLiP and released ipd
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- The scar on Chokrak mountain, Tajikistan, and the landslide that destroyed Khait village. Published by R.L. Wesson (USGS) and ipd

Table 6.12. Landslide and rockfall risk reduction methods
- Global landslide hazard map compiled by NASA. From https://earthobservatory.nasa.gov/images /89937/a-global-view-of-landslide-susceptibility
- Slope stability equipment near Sprey Point, Holcombe, Devon. Derek Harper under CC BY-SA 2.0 Unported licence
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- Wire mesh attached with rock bolts over a crumbling rock face near Teignmouth, Devon. Derek Harper under CC BY-SA 2.0 Unported licence
- A cutting stabilised by shotcrete, Brincliffe, Sheffield, South Yorkshire. Peter Kennett
- Retaining wall under repair, Knutsford, Cheshire. Schlosser67 under CC BY-SA 2.0 Unported licence
- Slope stabilised with gabions in a supermarket carpark, Sheffield, South Yorkshire. Peter Kennett
- Barriers used to catch boulders, Ecclesall Road, Sheffield South Yorkshire. Peter Kennett
- Rockfall protection shelter over the road and railway on the Kyle of Lochalsh to Lochcarron Road in Highland Region, Scotland. Trevor Wright under CC BY-SA 2.0 Unported licence
- Rip rap boulders dropped on the coast in East Sussex, to protect Fairlight village above. Nigel Chadwick under CC BY-SA 2.0 Unported licence

Table 6.13. Soil erosion
- Soil erosion in the Otter Valley, Devon. Peter Kennett
- Wind erosion of dust across the Fens, called locally a fen blow, across Hod Fen Drove near Yaxley, Cambridgeshire. Michael Trolove under the CC BY-SA 2.0 Unported licence
- Farm machinery buried by windblown dust in Dallas, South Dakota, USA, in 1936. Published by Sloan, a US Department of Agriculture employee, and so ipd

Table 6.14. Methods of reducing coastal erosion
- Rocky groyne at Hengistbury Head, near Mudeford, Dorset. Jim Campion under CC BY-SA 2.0 Unported licence
- Curved seawall used to deflect waves away from land. Leasowe, Wirral, Merseyside. Maggie Williams
- Rip rap protecting the coast, Dawlish Warren, Devon. Derek Harper under CC BY-SA 2.0 Unported licence

- Tetrapods protecting a sea wall at Ventnor, Isle of Wight. Martin Speck under CC BY-SA 2.0 Unported licence

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- Inert building waste at a waste transfer station, Ince-in-Makerfield near Wigan, Greater Manchester. David Long under CC BY-SA 2.0 Unported licence
- Domestic waste, Dogsthorpe, Peterborough, Cambridgeshire. Michael Trolove under CC BY-SA 2.0 Unported licence
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- Drigg low level radioactive waste disposal site from the air, near Sellafield, Cumbria. Thomas Nugent under CC BY-SA 2.0 Unported licence

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- Charity, an engineering geologist surveying the Cowburn Railway Tunnel, Derbyshire. Charity Rose
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- Geomorphologists measuring sediment transport across the Dee tidal flat estuary off the Wirral in Merseyside. Dan Parsons
- Vibroseis trucks generating shock waves for a seismic profile, operating in the Rivelin valley, Sheffield. Peter Kennett
- A Yorkshire Water hydrogeologist taking water samples. Credit, Yorkshire Water
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- Palaeontologist leading a group searching for dinosaur footprints. Coast near Burniston, Yorkshire. Peter Kennett
- Louisa, a research geologist in the rock deformation laboratory at the University of Liverpool. Peter Williams
- Sediment size analysis in the lab, Naval Oceanographic Office, Mississippi, USA. This file is a work of a sailor or employee of the US Navy, taken or made as part of that person's official duties. As a work of the US federal government, the image is ipd
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- A teacher discussing fieldwork. Peter Kennett
- Testing samples in the crater of Mutnovsky Volcano, Kamshatka, eastern Russia. Published by Dr Jake Maule under CCA-SA 3.0 Unported licence

Table 7.2. Methods used to observe and record the environment to observe and record geoscientific features

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- Landscape observation in the Dales, Yorkshire. Photo: Peter Kennett
- Satellite image of a folded sequence of Carboniferous rocks, Pendle Hill, Lancashire. Google Earth™
- Measuring the dip of a bed. Peter Kennett
- Measuring bed thicknesses in the Ecclesall Woods, Sheffield. Peter Kennett
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- The Earth Science Education Unit rock description key. By permission of ESEU
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- Recording a field diagram on the metamorphic aureole of the Shap Granite in Cumbria. Peter Kennett
- Annotated photograph of the Hardegsen Unconformity at Thurstaston Hill, Wirral, Merseyside. Maggie Williams
- Stratigraphic log of the Cleveland Ironstone Formation as seen at Staithes in North Yorkshire. Cliff Rigg under CCA 3.0 Unported licence
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- Using an auger to extract soil samples, Ecton, Staffordshire. Peter Kennett
- A Yorkshire Water scientist taking water samples. Credit, Yorkshire Water
- Device for sampling the water column in the ocean. Published at http://www.scienceimage.csiro.au/pages/about/ under CCA 3.0 Unported licence

Table 7.3. Building geoscience observations into models and maps
- A diorama of Bradford on Avon's fascinating geological history by Alan Bentley. Elizabeth Devon
- Large feldspar crystals in a finer-grained background igneous rock – showing two-stage cooling. Shap Granite, Shap, Cumbria. Maggie Williams
- The unconformity between Devonian rocks below and Triassic rocks above, Portishead coast, Somerset. Photo and diagram, Peter Kennett
- Geological map of the Strathaird Peninsula, Elgol, Skye, Scotland by Sean Collier, with thanks to Maggie Williams
- Geological cross section of the Strathaird Peninsula, Elgol, Skye, Scotland by Sean Collier, with thanks to Maggie Williams
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Boxes in Exploring Geoscience across England volume (designated E)

Box 0.1E. Localities mentioned in the English 'interest boxes' in this book
- The Google map containing this information can be found at: https://www.google.com/maps/d/u/0/edit?hl=en&mid=1fW_Ubko0_IFhJ9EI0GUU7Drhn4Gl_fPU&ll=52.53727430134915%2C-6.078488800000006&z=6

Box 3.1E. William Smith – the 'Father of English Geology'
- William Smith image and map both in ipd due to their ages

Box 3.2E. The Chronicles of Charnia
- *Charnia masoni.* Andy Dingley under CCA-SA 3.0 Unported license
- What Charnia may have looked like. Nobu Tamura under CCA-SA 4.0 International license

Box 3.4E. Arthur Holmes – radioactive dating <u>and</u> a mechanism for plate tectonics
- Arthur Holmes from https://geologyglasgow.org.uk/archive/arthur-holmes/ with permission
- Blue plaque on the home of Holmes. HJ Grey under CCA 2.0 Generic license

Box 3.3E. Geological period namers
- Permian – Roderick Murchison
- Carboniferous – William Conybeare and William Philips
- Devonian – Adam Sedgwick and Roderick Murchison
- Silurian – Roderick Murchison
- Ordovician – Charles Lapworth
- Cambrian – Adam Sedgwick

All images ipd due to their ages

Box 4.1E. The mineral fluorite

- Fluorite fluorescing. Didier Descouens under CCA-SA 4.0 International license
- Blue John bowl, Derbyshire Visitor Centre. Pasicles under CC0 1.0 Universal Public Domain Dedication

Box 4.2E. Prehistoric carvings on rock faces
- Prehistoric labyrinth carvings, Rocky Valley, Cornwall, England. Chris King.
- Cup and ring marks, Wallridge Moor, Northumberland. Andrew Curtis under CC BY-SA 2.0 Unported licence
- Rock art on Chattonpark Hill, Northumberland. Andrew Curtis under CC BY-SA 2.0 Unported licence

Box 4.3E. Chirotherium tracks – a fossil mystery that took more than a century to solve
- Plaster cast of Chirotherium footprints. Chris King
- Chirotherium tracks. Osama Shukir Muhammed Amin under CCA-SA 4.0 International license

Box 4.4E. Mary Anning, 'a woman in a man's world'
- Mary Anning with her dog Tray on Lyme Regis beach in Dorset, 1842, ipd because of its age
- The Plesiosaur skeleton found by Mary and Joseph Anning in 1830, ipd because of its age

Box 4.5E. Plateau hill forts
- Cadbury Castle hill fort, Somerset on a Jurassic limestone plateau. Joe D, modified by JimChampion under CCA-SA 2.5 Generic license
- Oswestry Iron Age hill fort. Oswestry Borderland Tourism under CC BY-SA 2.0 Unported licence
- Hambledon Hill iron age hill fort in Dorset. Marilyn Peddle under CC BY-SA 2.0 Unported licence

Box 4.6E. Abandoned millstones.
- Stanage Edge millstones. Peter Kennett.

Box 4.7E. The Whin Sill – a dolerite sill underlying Hadrian's Wall
- View to the east of the scarp face of Whin Sill (Peel Crags) © K.E. Thornton, NERC, BGS
- Whin Sill diagram. Elizabeth Devon

Box 4.8E. The metamorphic aureole of the Skiddaw granite
- Map from the Liverpool University geohub at: https://geohubliverpool.org.uk/wp-content/uploads/2020/04/Metamorphism-for-A-level-students-v2.pdf, with the permission of John Wheeler (after Eastwood 1968 – Geology of the country around Cockermouth and Caldbeck).
- Slate with andalusite. Pete Loader

Box 4.9E. A slate lithophone
- Lithophone photo. Elizabeth Devon

Box 4.10E. Walking over an oceanic plate in Cornwall
- Sheeted dykes on the Lizard, Cornwall. Anne Burgess under CC BY-SA 2.0 Unported licence
- Layered cumulate rocks, Coverack, Cornwall. Ashley Dace under CC BY-SA 2.0 Unported licence
- Serpentinite cliff, altered mantle peridotite, Kynance Cove, the Lizard, Cornwall. Pierre Terre under CC BY-SA 2.0 Unported licence

Box 4.11E. Vine, Matthews and sea floor spreading
- Vine and Matthews image from https://www.geolsoc.org.uk/Plate-Tectonics/Chap1-Pioneers-of-Plate-Tectonics/Vine-and-Matthews
- McKenzie, Matthews and Vine image from: https://www.balzan.org/en/prizewinners/mckenzie-matthews-vine with permission from the archive of the International Balzan Foundation

Box 4.12E. Dan Mckenzie and the plate tectonic mechanism
- Dan McKenzie image from https://www.mckenziearchive.org/biograph

Box 4.13E. The Permo-Triassic aquifer in North West England
- Cross-bedded desert dune sands of the Triassic Sandstone, Hilbre, Wirral. Maggie Williams
- Specimen of the Permo-Triassic sandstone. Maggie Williams

- SEM image of a Permo-Triassic sandstone showing the pore spaces between the grains. Maggie Williams
- Birds on the shore of Martin Mere, Lancashire. Lesbardd under CCA-SA 4.0 International license

Box 4.14E. The London aquifer – originally artesian flow
- Trafalgar Square fountains in London today. Diliff under CCA-SA 3.0 Unported license

Box 4.15E. Polluted mine water from a flooded deep coal mine
- Polluted water flowing from an old mine tunnel, Spittal. Elizabeth Devon

Box 4.16E. Evolution triggered by pollution
- Pale- and dark-coloured peppered moths. Both published by Chiswick Chap under CCA-SA 2.5 Generic license

Box 5.1E. Building stones in England
- Carboniferous sandstone block. Peter Kennett
- Granite pumping house and gatepost, Cornwall. Peter Kennett
- Cadeby Quarry. Courtesy of Blockstone Ltd
- Carboniferous sandstone walls and 'stone slates'. Peter Kennett
- Delabole slate quarry, Cornwall. Chris King
- Delabole slates used for roofing and walls, Tintagel, Cornwall. Chris King

Box 5.2E. The box stone mines
- Box stone mine with an old block crane. Nick Chipchase under CC BY-SA 2.0 Unported licence
- The Georgian Circus at Bath, Somerset (1754-68). Colin Smith under CC BY-SA 2.0 Unported licence

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- Old lime kiln on Kepworth Moore, near Northallerton, Yorkshire. Stephen Horncastle under CC BY-SA 2.0 Unported licence
- Disused lime kiln near Wells, Somerset. Sharon Loxton under CC BY-SA 2.0 Unported licence
- Industrial scale limekiln near Millers Dale, Derbyshire. Andrew Hill under CC BY-SA 2.0 Unported licence

Box 5.4E. Cheshire salt and the UK's largest rock salt (halite) mine
- Winsford Rock Salt Mine in Cheshire. Christine Johnson under the CC BY-SA 2.0 Unported licence
- Brine pump near Warmingham, Cheshire. Stephen Craven under the CC BY-SA 2.0 Unported licence

Box 5.5E. Glass making in St Helens, Lancashire
- The Palm House at Royal Botanic Gardens, Kew, London. Diliff under CCA-SA 3.0 Unported license
- Metropolitan Cathedral of Christ the King, Liverpool. Maggie Williams

Box 5.6E. Mining iron ore
- Sharkham Point iron mine near Brixham, Devon. Partonez under CCA-SA 4.0 International license
- A walking dragline extracting iron ore near Scunthorpe in the 1980s. Peter Kennett

Box 5.7E. Mining lead ore
- Magpie Mine, Sheldon, Peak District, Derbyshire. Peter Kennett
- Galena and barite in a brecciated limestone. Peter Kennett
- The main lead ore fields map. Courtesy of Northern Mine Research Society

Box 5.8E. Metal mining prospects in England
- Active metal prospects in England map by Ben Lepley, based on an infographic by the Critical Minerals Association

Box 5.9E. Fracking in the Fylde
- Shale gas exploration rig, Far Banks, Lancashire. K A under CC BY-SA 2.0 Unported licence

Box 5.10E. Opencast coalmine landscape remediation **–** Northumberlandia
- Northumberlandia Map. Oliver Dixon under CC BY-SA 2.0 Unported licence
- Northumberlandia photos. Maggie Harker

Box 5.11E. Morecambe Bay - Britain's second-largest natural gas field
- Morecambe Bay Central Processing Platform (CPP) and Morecambe Bay gas platform. Both published by Rossographer under CC BY-SA 2.0 Unported licence

Box 5.12E. Offshore wind power
- Rampion offshore wind farm, off the coast of East Sussex on a calm day. Wpwh81 under SSA-SA 4.0 International license
- Kentish Flats Wind farm. Rob Farrow under CC BY-SA 2.0 Unported licence
- Thanet Offshore wind farm, Kent. Rodw, released ipd

Box 5.13E. Geothermal energy in Cornwall
- United Downs Deep Geothermal Power Project diagram. Redrawn from: https://www.geoscience.co.uk/post/45-years-of-geothermal-in-cornwall-some-unanswered-questions-from-tony-batchelor

Box 5.14E. A site for the deep geological disposal of high-level radioactive waste – Sellafield?
- Sellafield nuclear power station, Cumbria. Simon Ledingham under CC BY-SA 2.0 Unported licence

Box 6.1E. Slumping and sliding on Mam Tor
- The Mam Tor landslide in 1985. Peter Kennett
- The old A625 across the Mam Tor landslip, Peak District, Derbyshire. Paul Stephenson under the CC BY-SA 2.0 Unported licence

Box 6.2E. A new way to show climate change - climate warming stripes
- All climate stripe images, compliments of the University of Reading

Box 6.3E. When England was connected to Europe – the million year old land bridge
- Early human footprints nearly a million years old, Happisburgh, Norfolk. Martin Bates under CCA 4.0 International licence
- Map redrawn from https://www.bbc.co.uk/news/10531419
- Palaeolithic stone tools excavated at Happisburgh, Norfolk, the earliest examples of tools found in Britain. Image from the Natural History Museum. Ethan Doyle White under CCA-SA 3.0 Unported licence

Box 7.1E. The Soham Murders Investigation – a crime solved by geoforensic evidence
- *Neoflabellina reticulata* from the chalk. Jonas Börje Lundin under CCA-SA 4.0 International license
- SEM image of the nannoplankton species *Gephyrocapsa oceanica.* NEON ja under CCA-SA 2.5 Generic license

Box 7.2E. 'Who dunnit?'
- All images, Maggie Williams