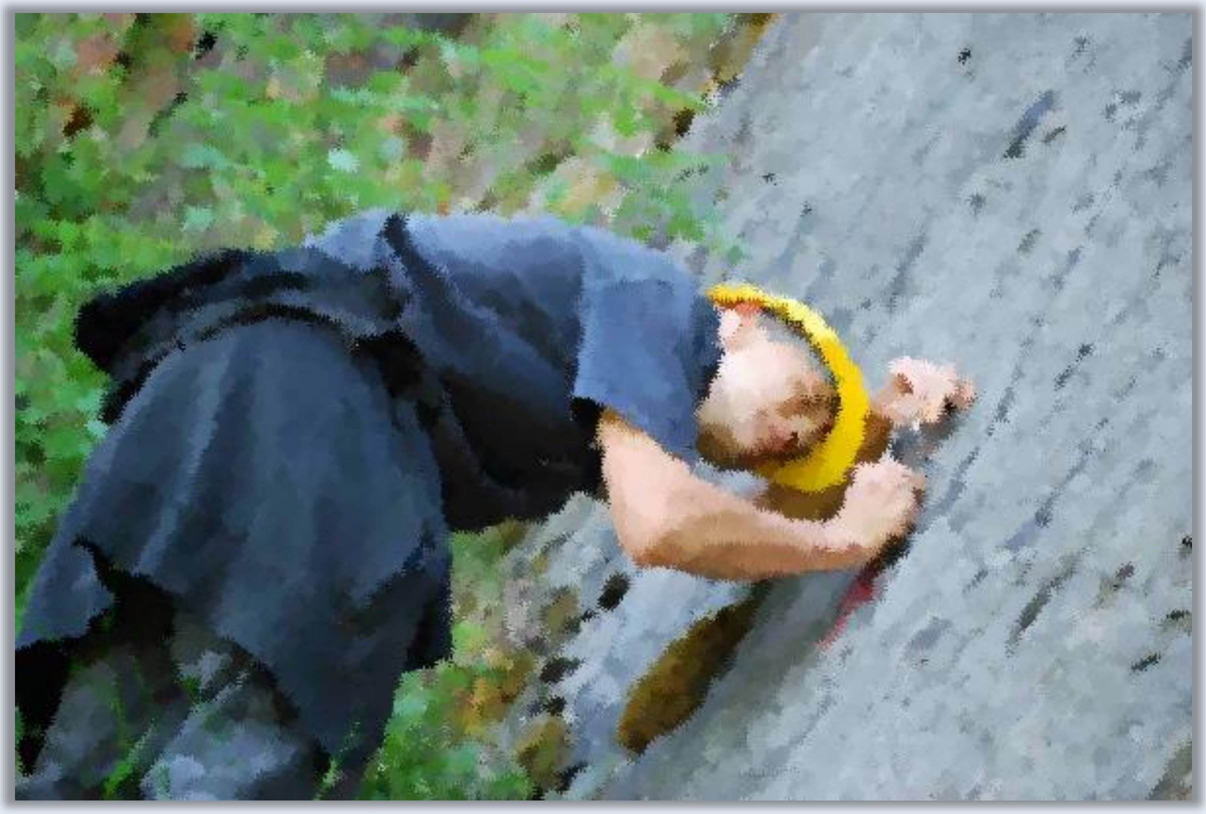
Exploring Geoscience – across the globe



Chris King

Approved by:
the International Geoscience Education Organisation
the International Union of Geological Sciences
the European Geosciences Union
for the teaching of the International Geoscience Syllabus

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First published: 2018
ISBN:
Published at: http://www.igeoscied.org/teaching-resources/geoscience-text-books/

Contents

Forward by Iain Stewart

Professor of Geoscience Communication and Director of the Sustainable Earth Institute, School of Geography, Earth and Environmental Sciences at Plymouth University, UK.

International surveys are showing that school-level education in geoscience across the world is very variable, the support offered to teachers of geoscience is generally poor, and the textbooks available in many countries are often deficient, and in some areas, non-existent.

So, against this rather grey backdrop, it is wonderful to be able to welcome the colour and vibrancy of the 'Exploring geoscience' textbook. It emerged from an initiative developed to underpin the International Geoscience Syllabus, and is championed by international organisations, including the International Geoscience Education Organisation, the International Union of Geological Sciences, and the European Geosciences Union.

This 'international version' of the textbook is an open source, free-to-download resource for use anywhere in the world by teachers, students and textbook-writers. It has been written to be as accessible and engaging as possible and also to be readily translatable into other languages. Once the 'international version' has been regionalised for other parts of the world, and translated, as necessary, then a new resource, checked by experts, will become available to support teaching and learning in geosciences.

It is a delight to be able to endorse this welcome and timely initiative and to encourage those interested in geoscience education across the world to take on the task of 'regionalising' and translating the textbook for use in their own regions, thereby spreading its exciting content and important message as widely as possible.

Iain Stewart.

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 is written as an 'international version' called '**Exploring Geoscience – across the Globe**' and is illustrated by photographs selected from across the globe and 'interest boxes' of global interest. It is published on the International Geoscience Education website at: http://www.igeoscied.org/teaching-resources/geoscience-text-books/. Geoscience educators across the globe have been 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.

The textbook is keyed into a separately published 'Activity Supplement', 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 International Geoscience Syllabus is published at: http://www.igeoscied.org/?page_id=269

Contributors and acknowledgements

We are grateful to Gillian Drennen (gillian.drennen@wits.ac.za) for first suggesting the writing of a textbook to address the international syllabus, and for proposing a workshop at the International Geological Congress, Cape Town in 2016 to develop this idea. We are grateful to all the contributors to that workshop for the ways in which they steered early ideas about the textbook.

The original text and many diagrams 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).

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.

We are most grateful to Peter Craig, Elizabeth and Martin Devon, Sid Howells, Peter Kennett, Pete Loader, Giulia Realdon, Tanja Reinhardt (Chapter 1), Ashvin Wickramasooriya and Sebastian Wolf (Chapters 1, 2) for all their work in checking the accuracy of the script, in helping to make the text more accessible and in proof-reading. We are also most grateful to Anthony Tibbs for his formal proof-reading efforts. Any remaining errors remain mine and mine alone.

The 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.

International Geoscience Education Organisation

Chris King.

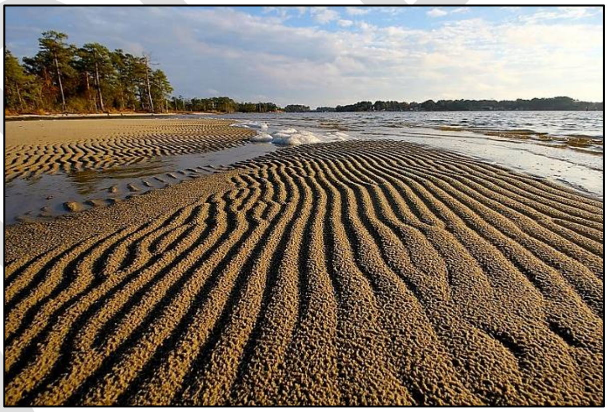
Exploring Geoscience – across the globe

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.



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.

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.

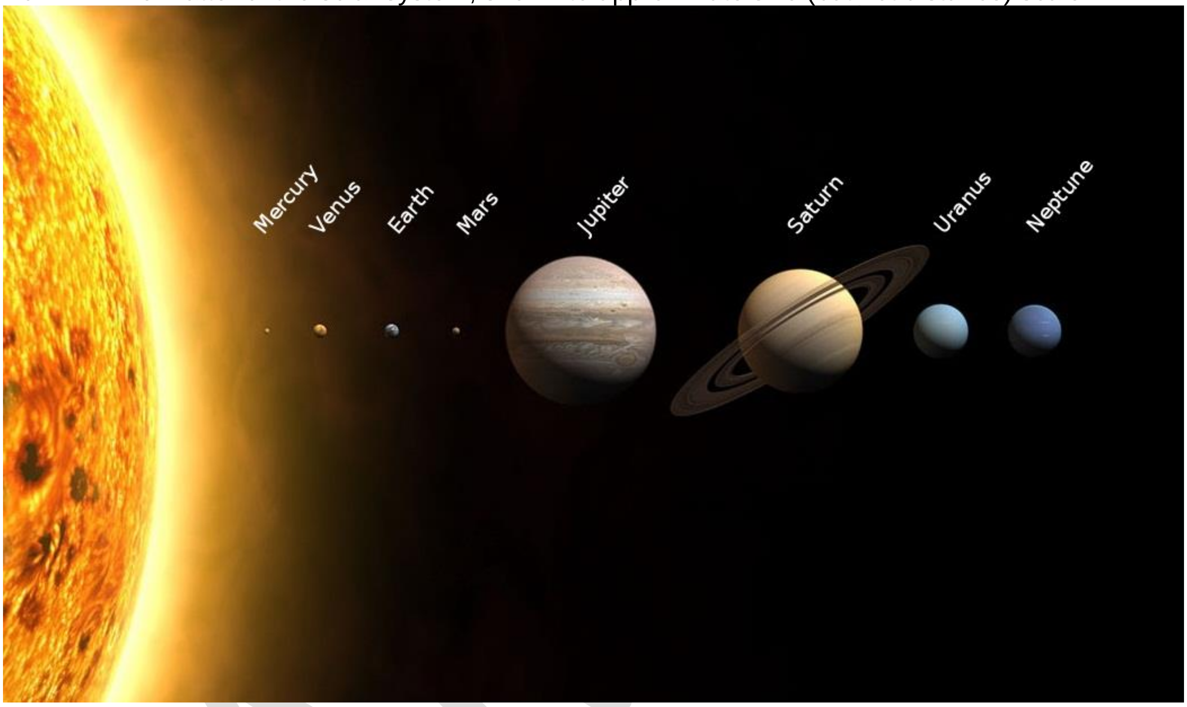
Figure 1.2. The Earth – a very complex system

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


Soil moisture


Groundwater spring

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.

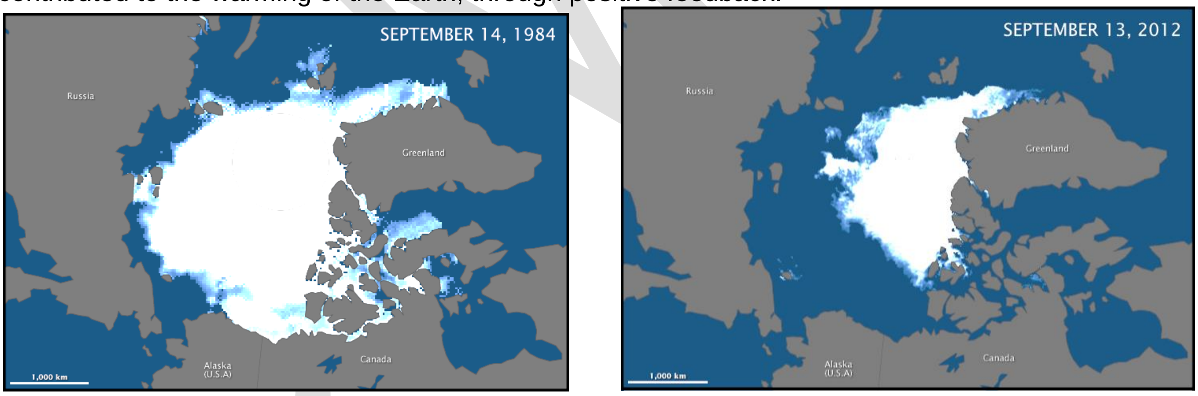
For example, the amount of salt in the oceans is affected by a negative feedback system. Rivers around the world dissolve salt (sodium chloride, NaCl, the mineral halite) from the surrounding rocks and carry it to the sea, but the saltiness (salinity) of the oceans stays the same (around 3.4% salt) when 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 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 sheet in 1984 and 2012. In the past, the large ice sheet had a large albedo effect. As Earth has become warmer, the ice sheet 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.

Figure 1.5. A simple water cycle demonstration

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.

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.

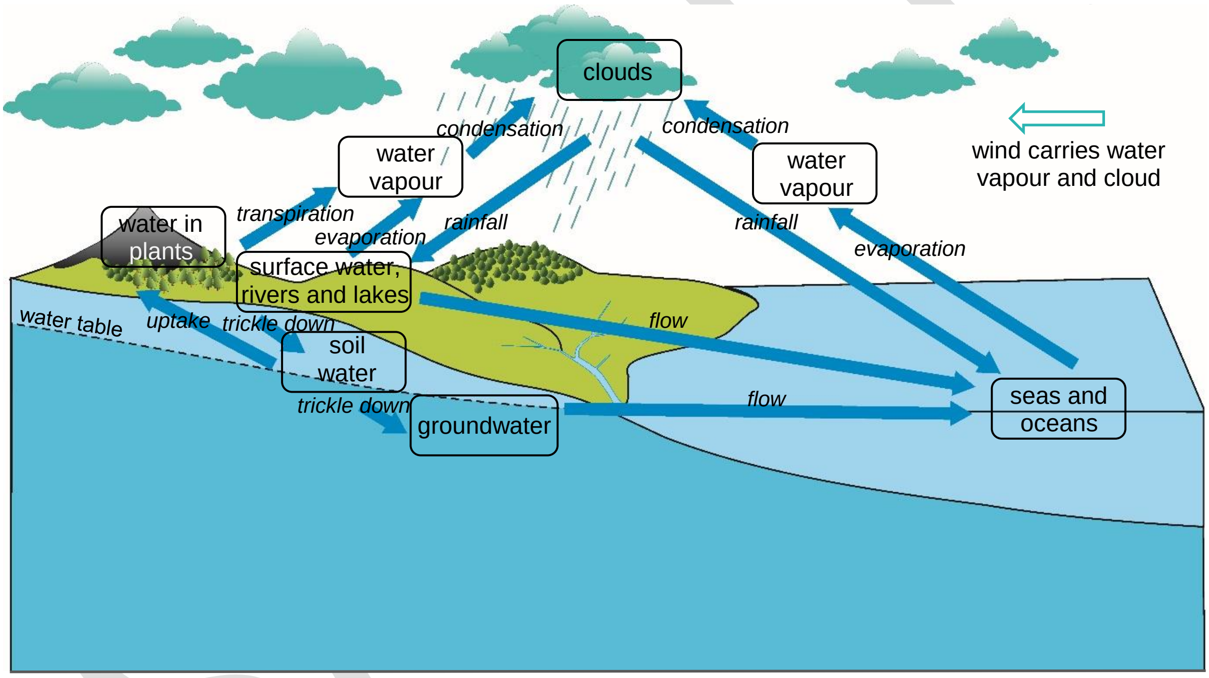
When it rains, water forms puddles on the ground. The puddles later evaporate into invisible water vapour in the air. When the air cools, the water vapour condenses into water droplets as clouds. As clouds continue cooling, the water droplets join together to form raindrops which, when they are large 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.

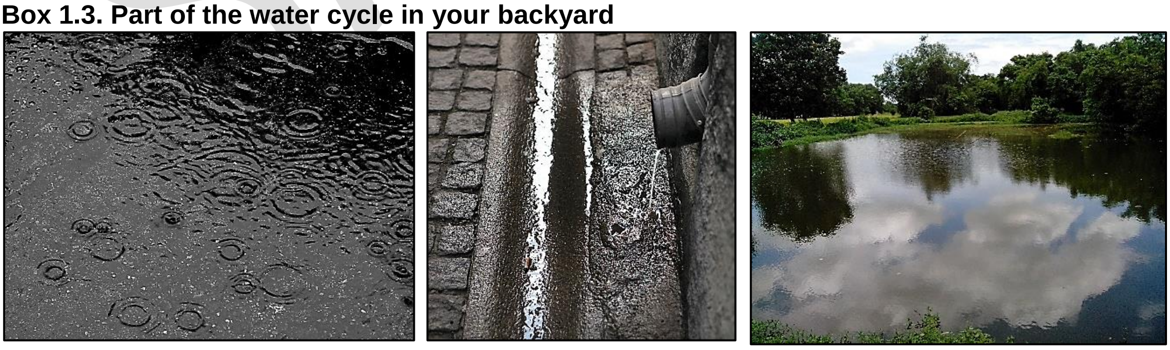
In cold regions, water falling as snow can build up into the ice of glaciers and ice sheets, while groundwater can be frozen in **permafrost** (permanently frozen ground). Ice can also flow, or melt to become liquid water again.

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 in your backyard



You can see part of the water cycle in action in your own backyard. 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 forms 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.

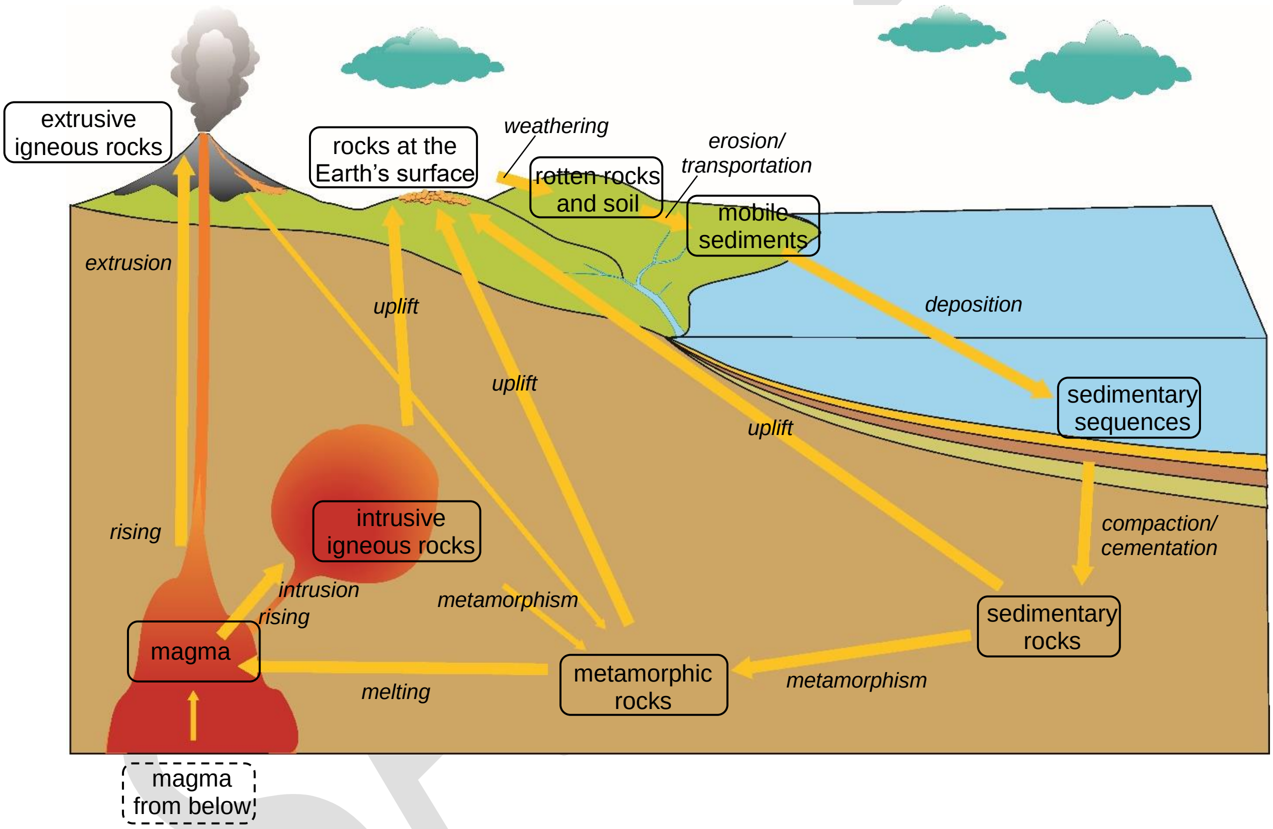
Figure 1.7. shows how the rock cycle products (in boxes) and processes (in italics) are linked together. Rocks at the Earth's surface are changed by weathering into rotten rocks and soil; when this material is eroded and transported it becomes mobile sediments. Deposition of mobile sediments builds up 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 this hiker is resting in the Alaskan tundra, he is 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 hiker ate the berries, this 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.

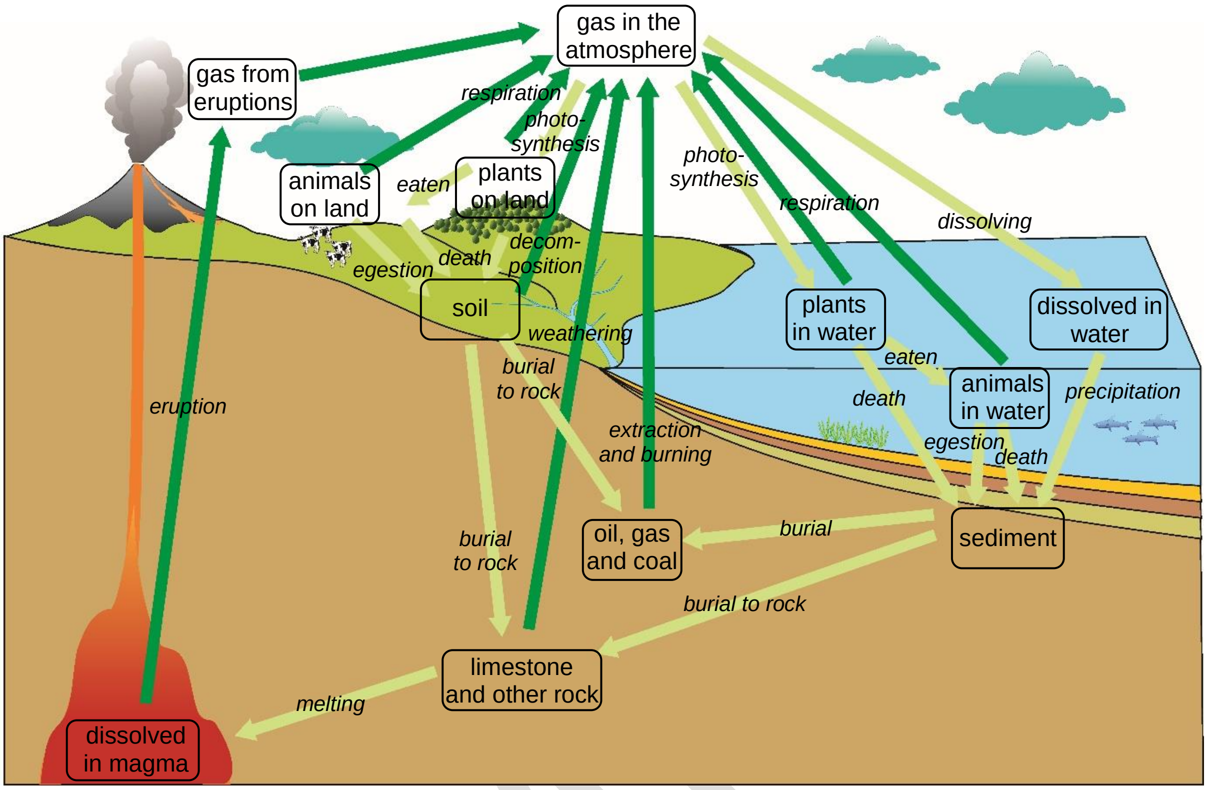
When plants die, they usually decay, but if they are buried by sediments and preserved, the carbon in them is also preserved. When land plants are preserved, thick layers can form coal, releasing natural gas as it matures. As microscopic animals and plants in the oceans die, they can also be preserved 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 in pale green, processes releasing carbon in dark green.



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 linked with the rotation of the Earth and 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 backyard.

You can see the stars of the universe, and some of the planets of the solar system, from your own backyard, 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.

A chapel in France under the Milky Way

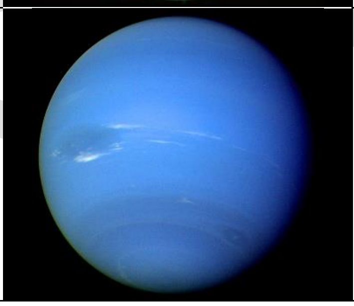
Star movement caught by an open shutter, Chile

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, ºC**	**Other features**
Mercury		57.9	4879	0.33	167	• No moons • Cratered surface • Terrestrial planet
Venus		108.2	12,104	4.87	464	• No moons • Covered by cloud • Cratered surface • Terrestrial planet
Earth		149.6	12,756	5.97	15	• One moon • Oceans • Some craters known • Terrestrial planet • Plate tectonics identified
Mars		227.9	6792	0.64	-65	• 2 moons • Cratered surface • Large volcano • Past sedimentary processes • Terrestrial planet

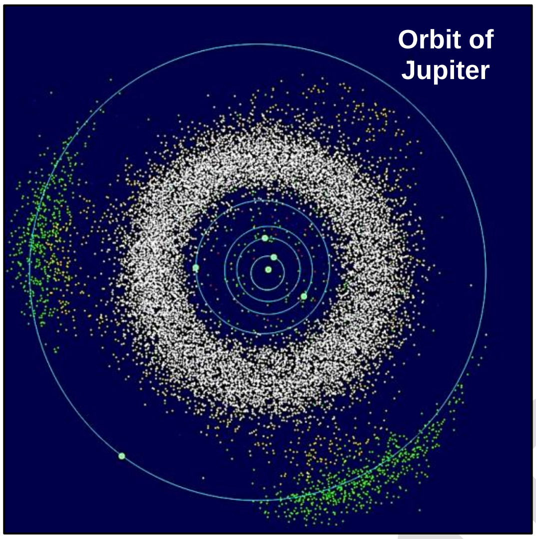
Table 2.1. Planets of the solar system, in order from the Sun, continued

Name	**Image** (not to scale)	**Distance from the Sun, million km**	**Diameter, km**	**Mass, 10^{24} kg**	**Mean surface temper-ature, °C**	**Other features**
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						

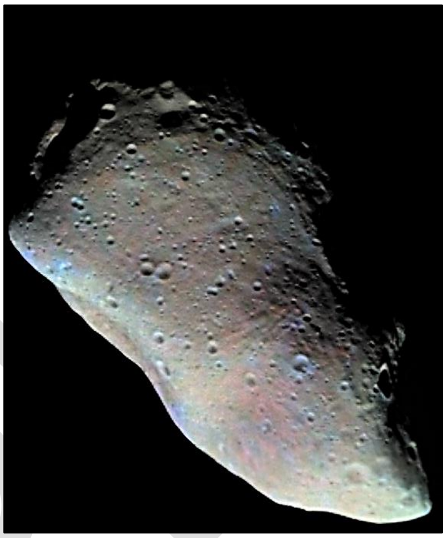
Our solar system not only contains planets and dwarf planets, but also belts of **asteroids** and **comets.** Many of the meteorites that hit the Earth and other planets originally came from the asteroid belt or from comets. Impacts from meteorites and larger bodies are one of the catastrophic events 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-Bop comet seen from Croatia in 1997

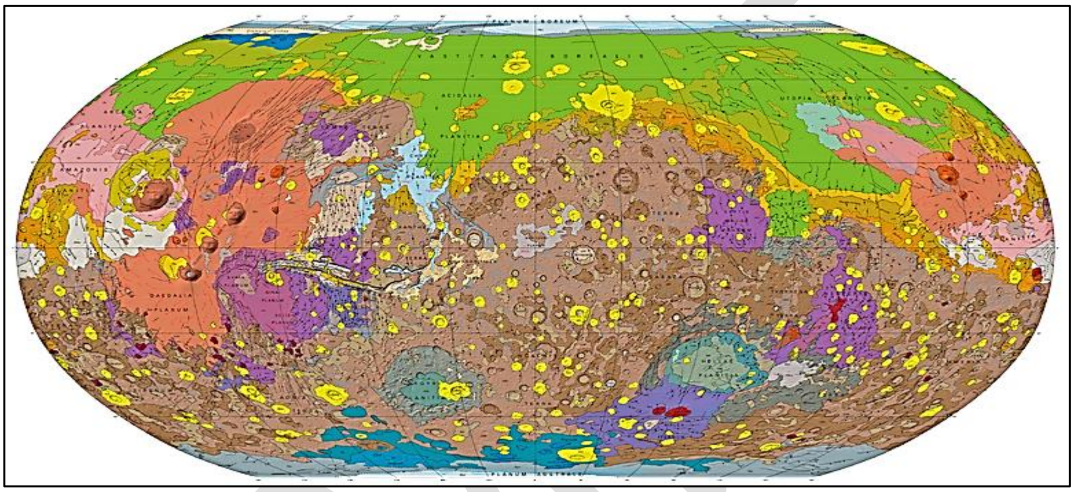
Comet Churyumov–Gerasimenko in September 2014 as photographed by the *Rosetta* spacecraft before the lander *Philae* landed on its surface

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.

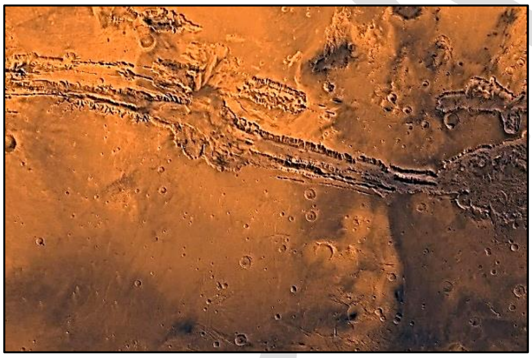
Box 2.4. Planetary geology – Mars

Before landing 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.

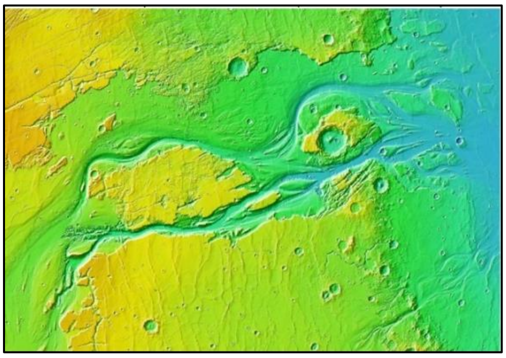
The landers have provided even more evidence of water flow, including sedimentary layers and rounded pebbles. The landers have also shown that most of Mars is cratered desert, covered by boulders and dust. Wherever the water is, that used to flow over the surface, it is not there now.



Geological map of Mars – green areas – lowland geology, reds and purples – volcanic rocks, blues are polar geology, brown and orange colours – highland rock areas, yellow – impact craters



The faulted canyon system near the equator



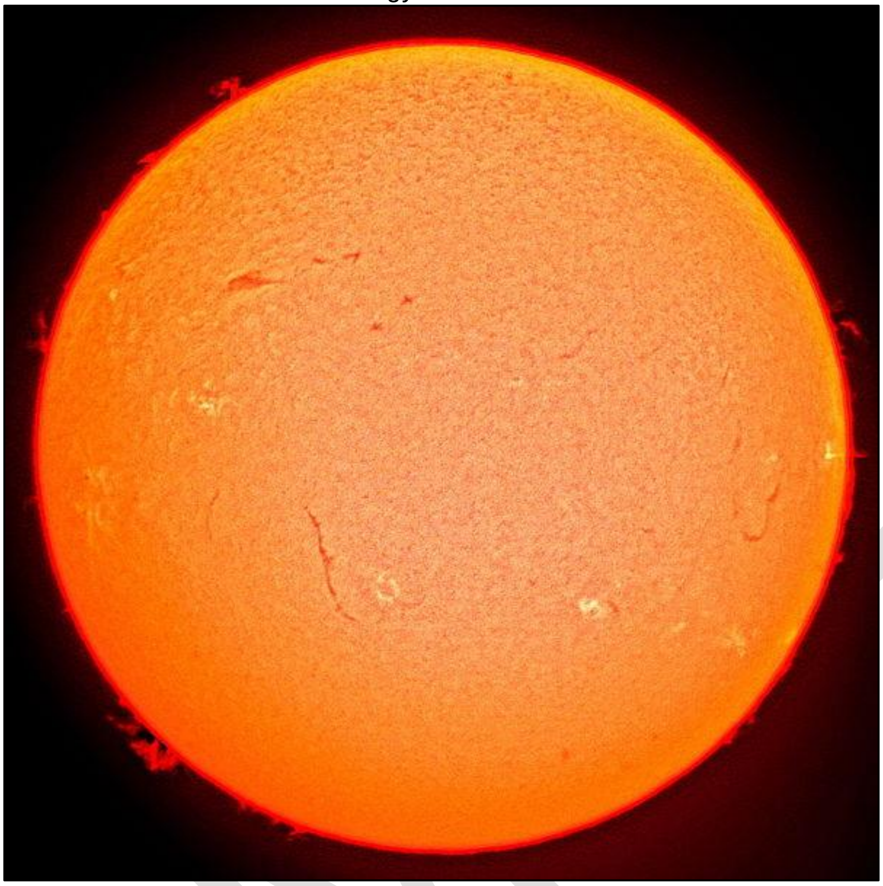
The Kasei Valles outflow channel

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.

Figure 2.2. The Sun – our main source of energy



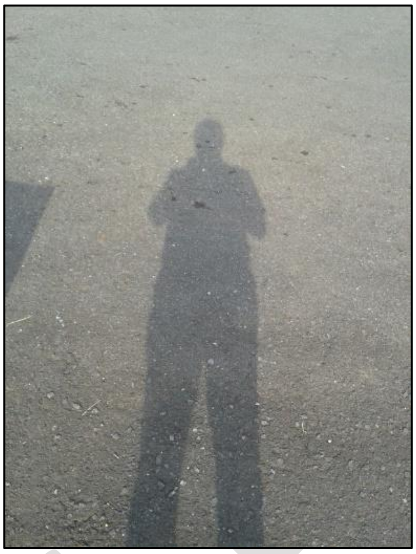
Energy from the Sun passes through space, mostly as visible light, infrared and ultraviolet radiation. When this energy warms land and ocean surfaces, some of it is radiated back and warms the atmosphere. Energy is received from the Sun during the day and is radiated back out into space at night. These 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%.

2.3. Sun, Earth and moon

2.3.1. Day/night

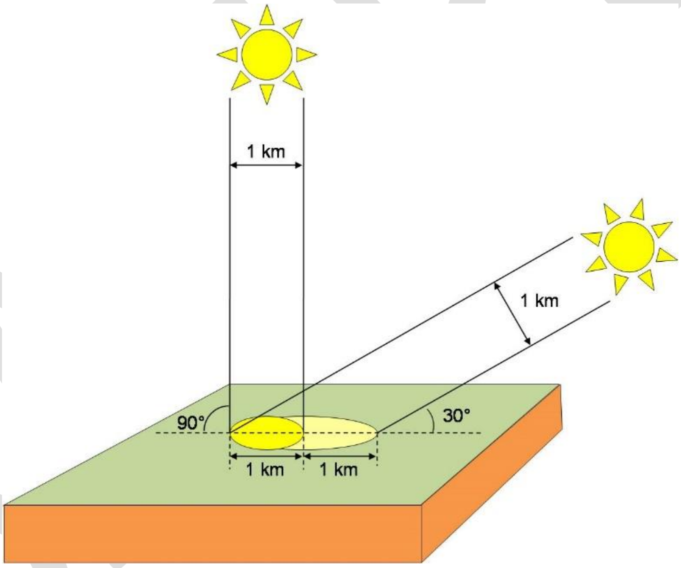
Earth receives energy from the Sun as ultraviolet, visible and infrared radiation, which heats the Earth. The heating is greatest when the Sun appears highest in the sky, as shown in Figure 2.3. When the Sun appears directly overhead, a 1km-wide beam of radiation heats a 1km-wide zone of the Earth, but when the angle of the Sun is 30º, 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 13.00 and the right-hand one at 16.00 at Ibadan in Nigeria.

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.

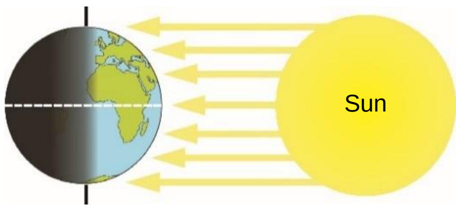
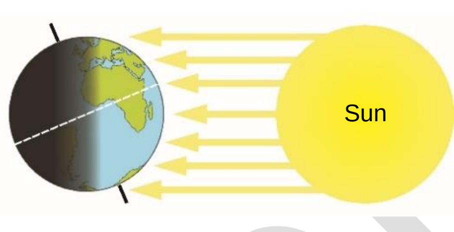
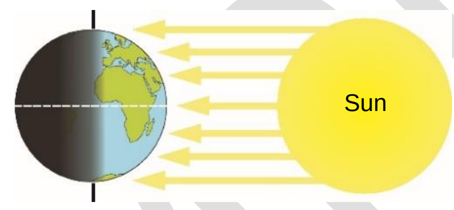
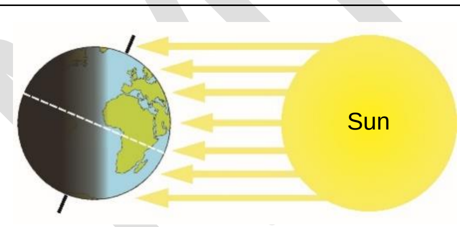
The amount of heat received depends on what the surface is like. Dark surfaces absorb and re-radiate more heat than pale-coloured surfaces, since the pale-coloured surfaces reflect more of the radiation; this is the albedo effect. Land heats up faster than water, because the water circulates the heat 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

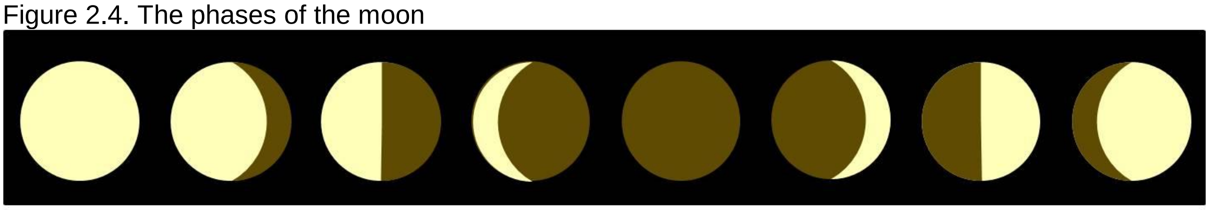
Hemisphere	**Season**	**Diagram**	**Angle of rays**	**Length of day/night**
March			**March**	
Northern	Spring		The same angle of rays and length of day/night everywhere on Earth	
Southern	Autumn			
June			**June**	
Northern	Summer		North warm because:	
			Sun high in the sky	Long days to receive Sun
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 says 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



Full moon ⟵⟶ Waning moon ⟵⟶ New moon ⟵⟶ Waxing moon

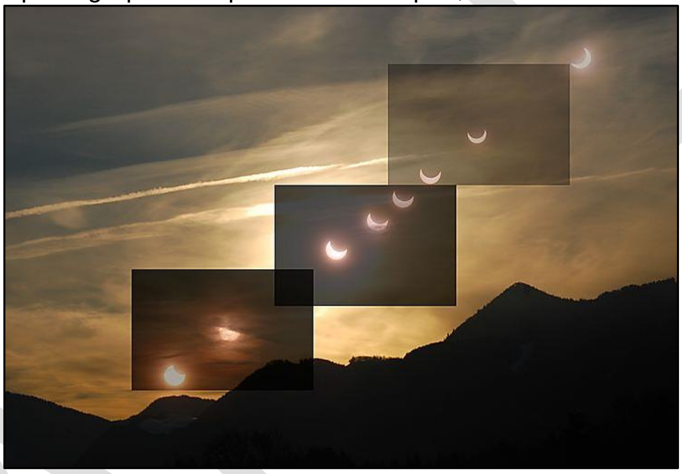
Figure 2.5. The moon becoming full – a collage of three photographs

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 in to 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

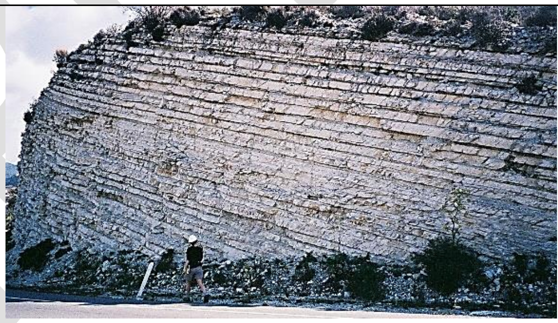
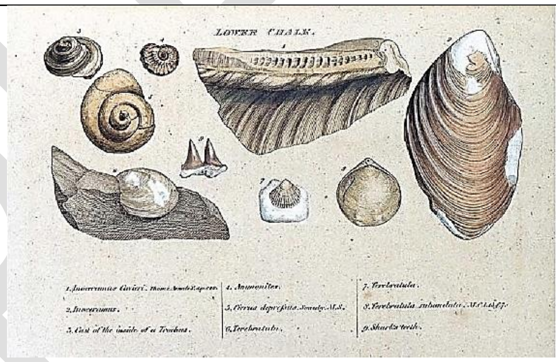
Relative dating method	First described by:	Details of method	Example
Principle of superposition of strata	Nicholas Steno in 1669	When rocks are laid down, those on top are the youngest (exceptions are, for example, when a sequence is overturned by deformation or when faulting has pushed an older sequence over a younger one)	 Tilted chalk in Cyprus – youngest on top  Folded rock in Greenland – the rock at top of the is island overturned, with older rock on top
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	 Dykes in Colorado, USA; grey rock oldest, cross-cut by near horizontal dyke, then by sloping dyke – youngest

Table 3.1. Relative dating methods, continued

Relative dating method	First described by:	Details of method	Example
Law of included fragments	Charles Lyell in 1830	Any fragment included in another rock must be older	 Herm, Channel Islands, UK; the xenoliths (included fragments) of dark rock in paler granite are older
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	 One of William Smith's drawings of a group of fossils used to date a rock
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	 An unconformity in Bochum, Germany. The un-deformed upper rock is younger than the deformed and tilted grey 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	 Miocene sediments laid down horizontally – Drahomyrchany, Ukraine	 Sediments not originally laid down horizontally – cross bedded (layered) sands laid down in the ice age. Estonia
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	 The laterally continuous sedimentary rocks of the Grand Canyon, Arizona, USA	 Non-continuous sediments, river deposits in Iceland – which 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.

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

- 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'

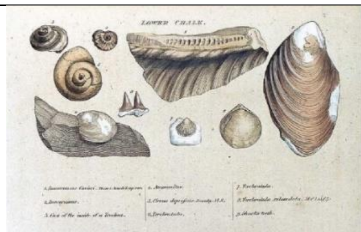
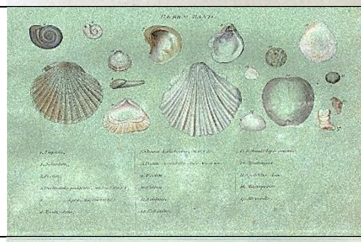
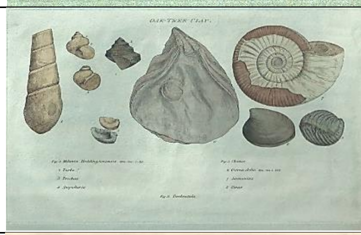
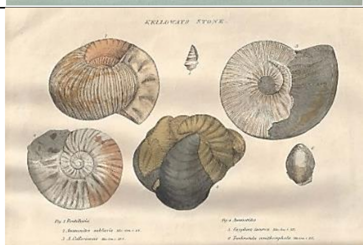
So the history of the rocks is:

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'

William Smith's sequence		**Age related to periods of the geological time scale, recognised after Smith**	**William Smith's original fossil group drawing**
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	

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.

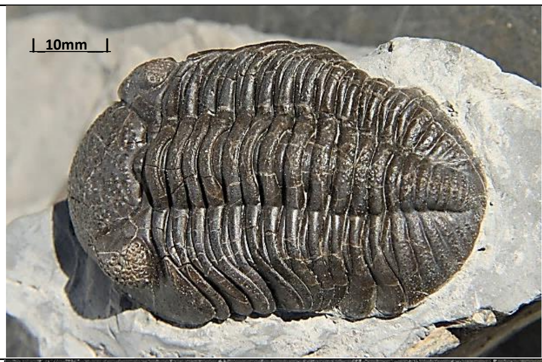
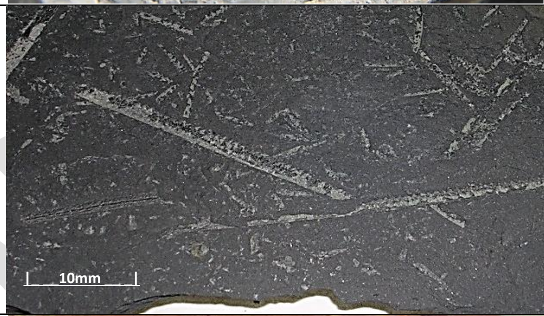
Table 3.4. Typical fossils found in rocks of different ages

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	*Crassostrea titan* oyster shell, which lived on rocky sea shores; this specimen from Santa Margarita Formation, California, USA	
Paleogene	Fossil teeth of the extinct sand tiger shark *Carcharias tingitana*; teeth of this shark are found only in the Palaeogene; these specimens from Khouribga, Morocco	
Cretaceous	*Micraster leskei* 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 Chalk near Puys, Dieppe, France.	

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	*Calliphylloceras* ammonite which lived like an octopus with a shell, swimming in the sea; the walls between the chambers had very complex shapes, shown by black paint here; these shapes are only found in Jurassic and Cretaceous ammonites 	
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 	
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	*Caninia* solitary rugose corals which lived rooted in the sea floor; these specimens are from the Lecompton Limestone, in Kansas, USA	

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	*Monograptus* graptolite with a single arm carrying a colony of graptolite animals; floated in the ocean	
Ordovician	*Tetragraptus* graptolite with four arms*; each of the arms carried a colony of small graptolite animals; the colony floated in the ocean; this specimen from the lower Ordovician Bendigoian Series, Bendigo, Victoria, Australia * only three of the four arms (stipes) can be seen in the photo	
Cambrian	*Paradoxides* trilobite; these lived on the sea floor and were probably predators	

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.

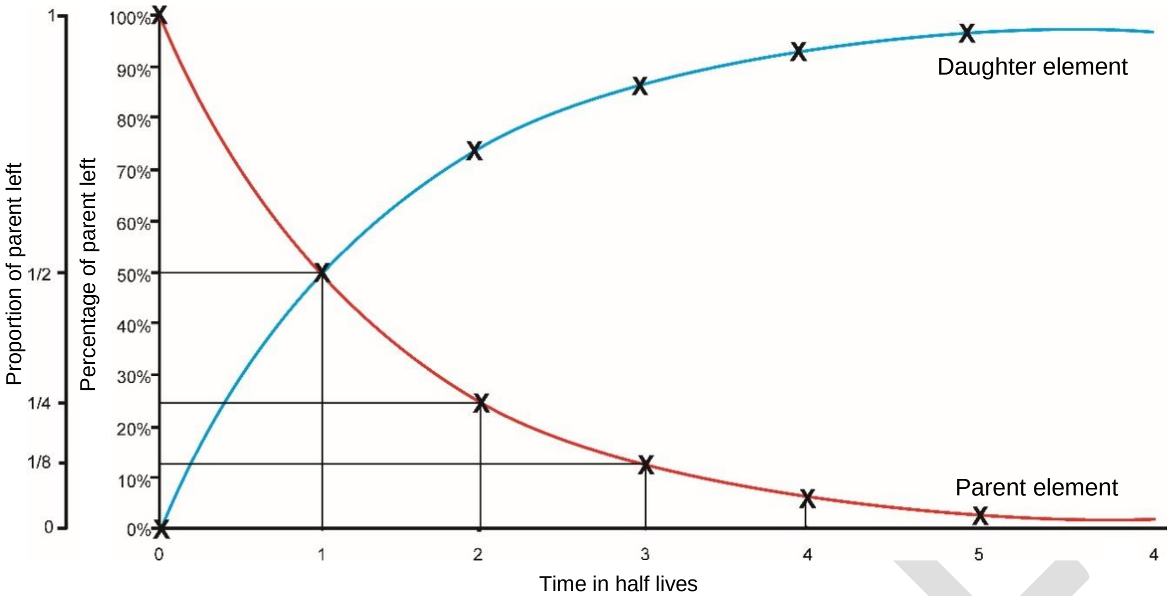
The 'golden spike' bronze marker at one of the geological boundaries within the Triassic Period – with a plaster cast of the ammonite which first appears in the geological record there, marking the boundary

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 77.5% 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.

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, since 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	Abbrev-iation	Age (Millions of years ago (Ma))	Major events
				0	
Phanerozoic	Cenozoic	Neogene	N	23	3.3 Oldest stone tools
Phanerozoic	Cenozoic	Paleogene	Pg	66	50 Himalayan mountains 66 K-Pg mass extinction
Phanerozoic	Mesozoic	Cretaceous	K	145	130 Early flowering plants
Phanerozoic	Mesozoic	Jurassic	J	201	160 Early birds 190 Opening of Atlantic Ocean
Phanerozoic	Mesozoic	Triassic	T	252	220 Early mammals 252 ‘Great dying’ mass extinction
Phanerozoic	Palaeozoic	Permian	P	299	299 Supercontinent Pangaea first formed
Phanerozoic	Palaeozoic	Carboniferous	C	359	315 Early reptiles
Phanerozoic	Palaeozoic	Devonian	D	419	370 Early amphibians
Phanerozoic	Palaeozoic	Silurian	S	444	
Phanerozoic	Palaeozoic	Ordovician	O	485	400 Early insects 430 Early land plants
Phanerozoic	Palaeozoic	Cambrian	Cm	541	530 Early fish 541 Life with shells and hard parts
Precambrian	Proterozoic			2,500	2,000 Early multicelled organisms 2,100 Early eukaryotes
Precambrian	Archaean			4,000	2,700 Free oxygen in atmosphere 3,500 Early bacteria and algae 4,000 Oldest known rocks
Precambrian	Hadean			4,600	4,6000 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.

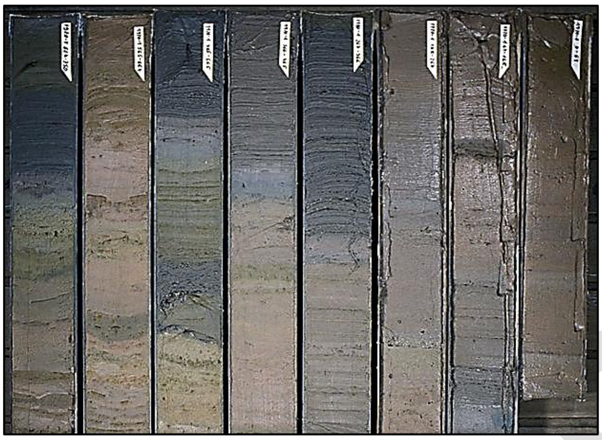
3.4 Rates of processes

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 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.

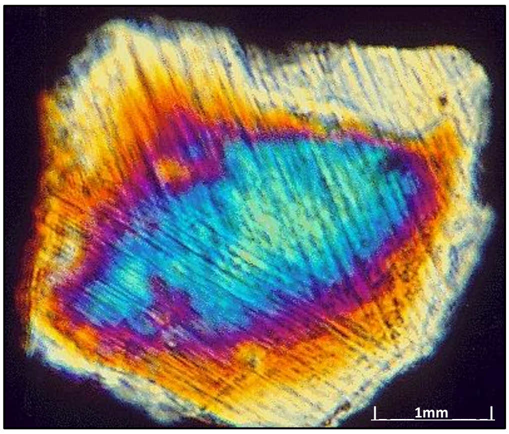


Cores of deep sea sediments from the deep sea near Greenland; the sediment layers have built up over long time-spans

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.

Common tektite shapes – dumbbell and teardrop



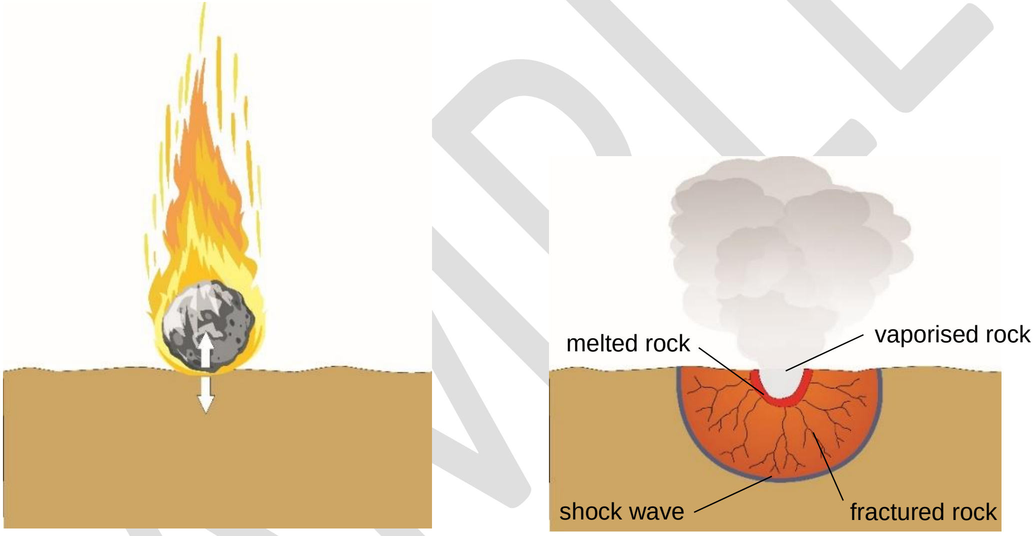
Shocked quartz with deformation planes seen under the microscope in cross-polarised light

Box 3.5. Catastrophic impact events, continued

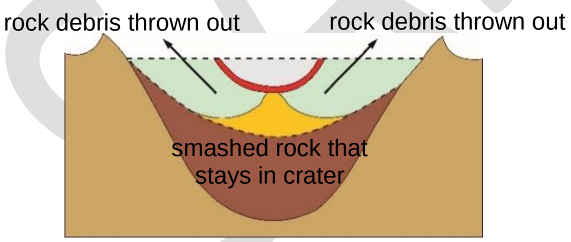
Lonar crater in India – produced by an impact thought to have been about 52,000 years ago

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

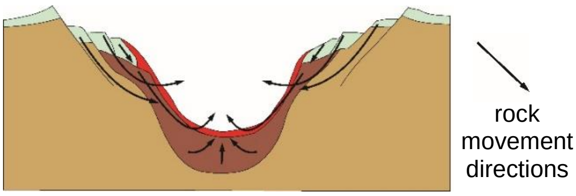
The geology of impacts is unusual because many of the events happen in seconds, rather than the much longer time spans usually studied by geologists. Impacts usually have the stages shown below. The result is the familiar crater shape, shown by Meteor Crater.



Stage 1 – contact and compression stage



Stage 2 – excavation stage



Stage 3 - modification stage

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.

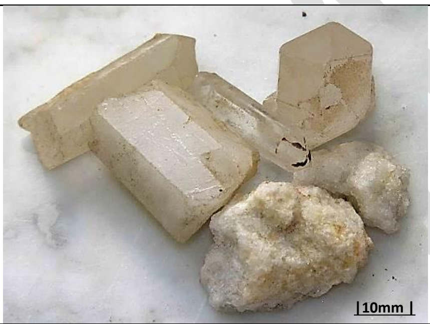
4.1.1. Earth materials and properties

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.

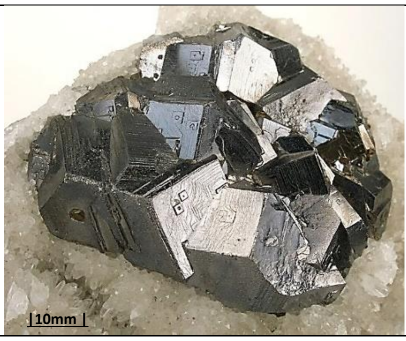
4.1.1.1. Minerals

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 Crystals from: Unknown locality		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 Crystals from: Rock Creek Canyon, Sierra Nevada, California, USA		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 Crystals from: Unknown locality		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

Name	Image	Chemistry	Shape of good crystals	Physical properties
Calcite Crystals from: Nkana Mine, Zambia		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: Wieliczka salt mine, Poland		Sodium chloride; NaCl	Cube-shaped	Colourless, white or pink; low hardness; very easily breaks into cube shapes; salty taste
Gypsum Crystals from: Unknown locality		Calcium sulphate; $CaSO_4.2H_2O$	Thin crystals, forms 'desert roses' like the one in the image	Colourless, white or pink; low hardness; easily breaks along flat surfaces
Pyrite Crystals from: Unknown locality		Iron sulphide; FeS_2	Often cube-shaped	Shiny brassy yellow; hard; difficult to break; high density

Name	Image	Chemistry	Shape of good crystals	Physical properties
Galena Crystals from: Gibraltar Mine, Naica, Chihuahua, Mexico		Lead sulphide; 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.

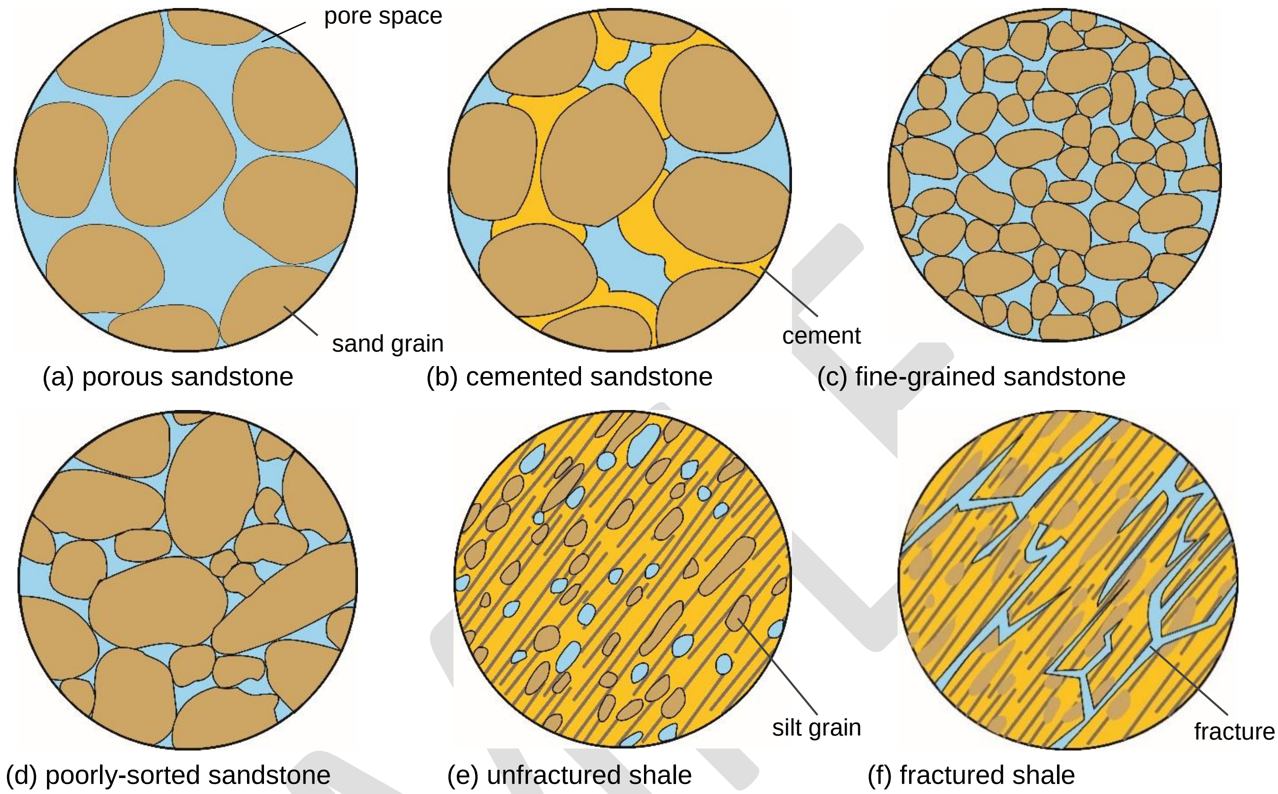
Diamonds are so special because strong atomic carbon bonds make them the hardest mineral on Earth. They also have a very bright shiny surface. Rough diamonds, like the one shown in the central photo can be cut to make them reflect the light even more, making them the most valuable gemstones, widely used 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.

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.

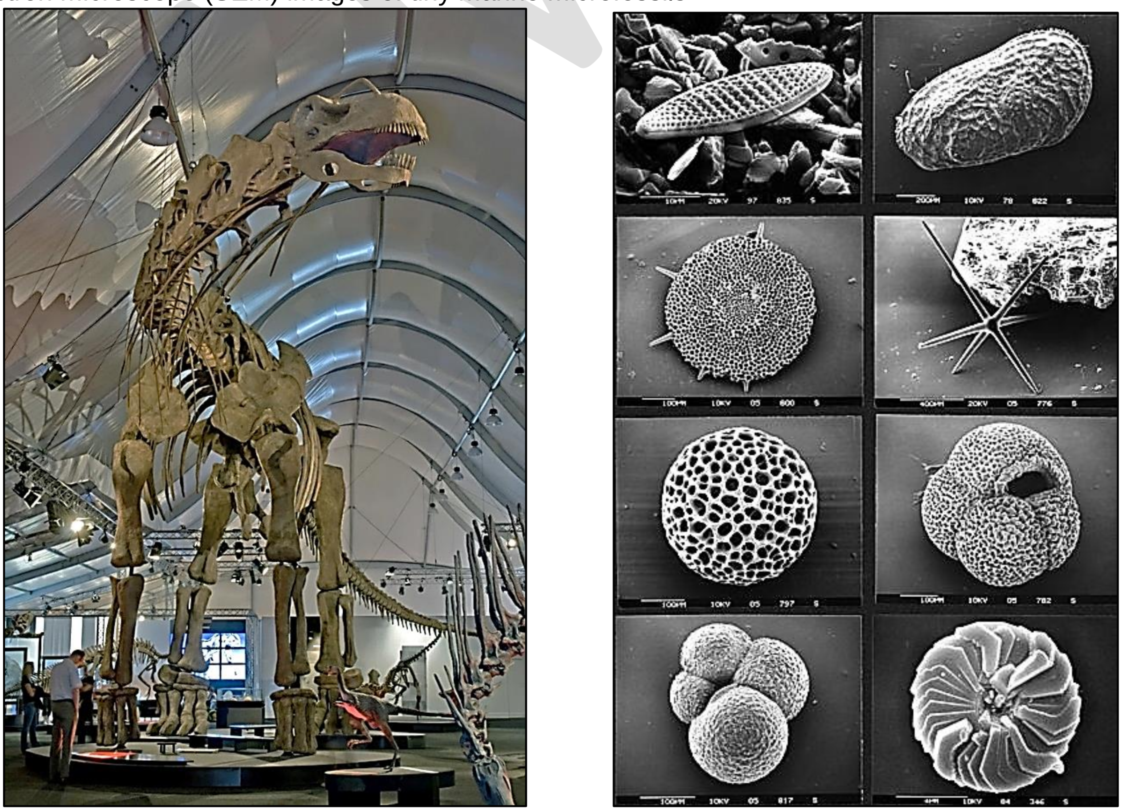
Table 4.2. The results of simple tests to distinguish the three main rock groups

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		

4.1.1.3. Fossils

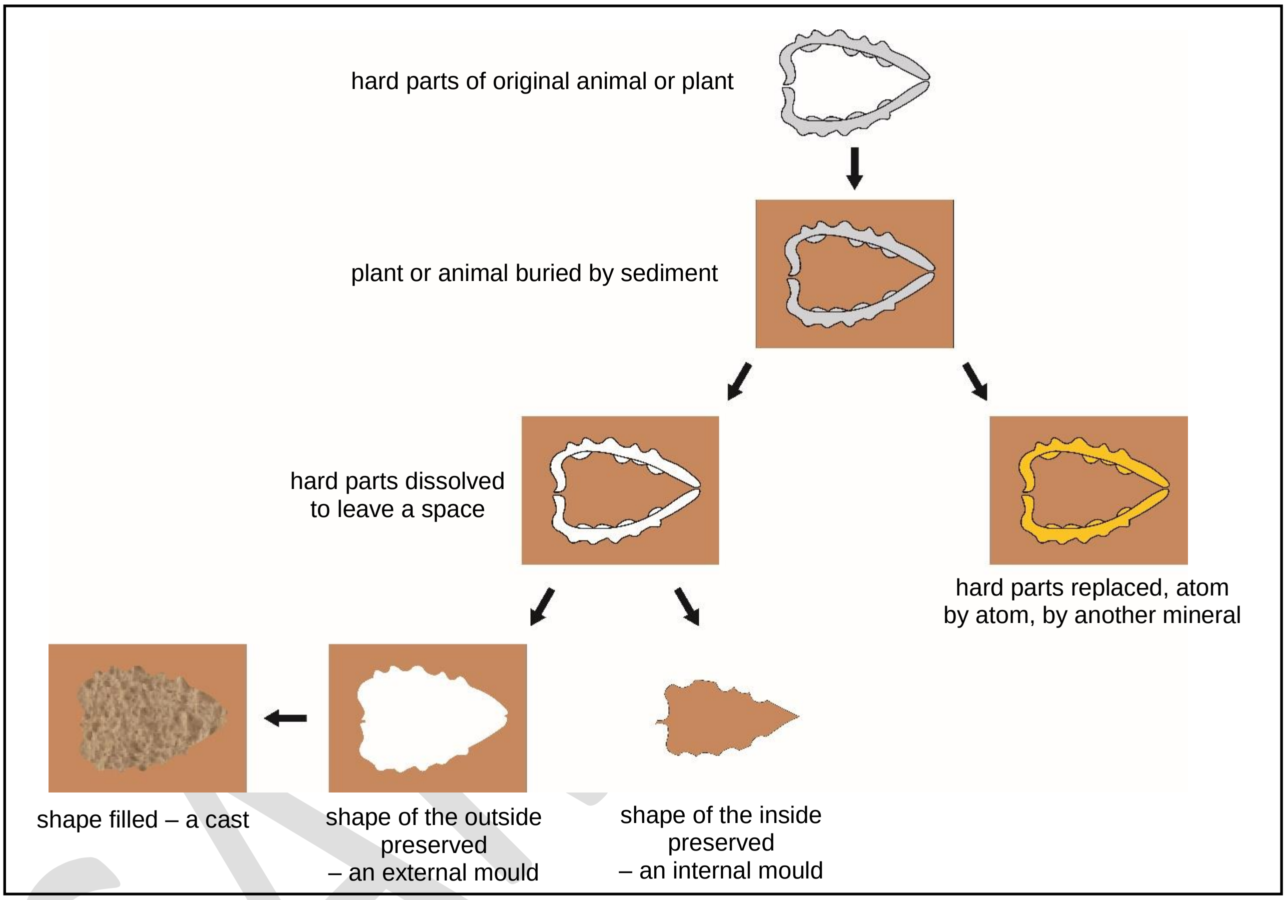
Fossils include any preserved trace of life and are usually considered to be more than 10,000 years old. They range in size from the largest dinosaurs to the smallest microfossils (Figure 4.2.).

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

Table 4.3. Important processes of fossilisation, continued

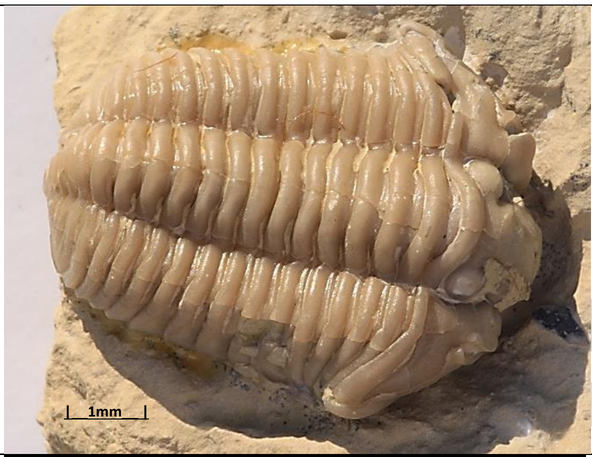
Fossilisation process	**Image**	**Fossil group**
Burial – hard parts only preserved		A *Calymene* trilobite Fossil from Henryhouse Formation, Oklahoma, USA Silurian age
Replacement – original mineral replaced by a new mineral		Ammonite, originally formed of calcium carbonate, now pyrite Fossil from Bully Calvados, France Jurassic age
Mould-formation		The internal and external mould of a snail-like gastropod (the fossil itself has been dissolved away, leaving the shape of the inside and outside of the shell) Fossil from Galena Formation, Iowa, USA Ordovician age
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, England Cretaceous age

Table 4.3. Important processes of fossilisation, continued

Fossilisation process	Image	Fossil group
Trace fossils – burrows and trails		Burrows and the resting-place of a trilobite Fossils from Gog Formation, Lake Louise, Alberta, Canada Cambrian age
Trace fossils – rootlet traces		Root traces of a fossil *Lepidodendron* plant (body fossil) with rootlet traces (moulds – trace fossils) Fossil from North-eastern Ohio, USA Carboniferous age

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 – 256 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

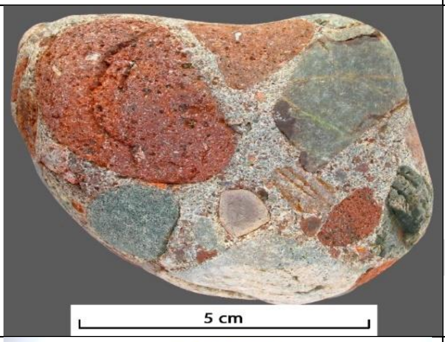
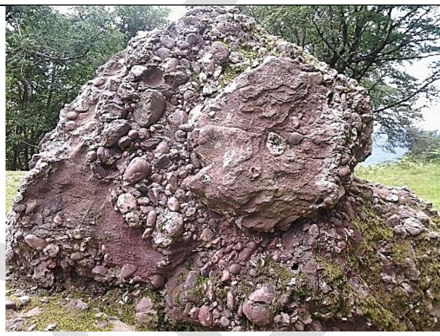
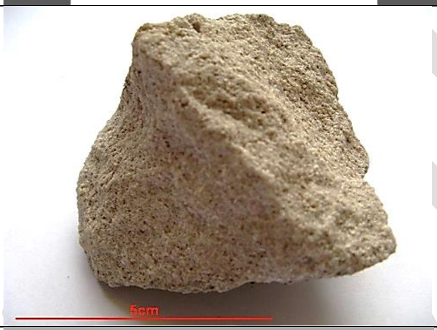
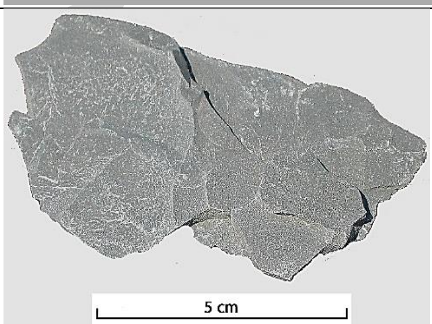
Sedimentary rock	Images		Source of exposure image
	Specimen	Exposure	
Conglomerate			Conglomerate exposure, near San Sebastian, Spain Cretaceous age
Cream sandstone			Cross-bedded cream sandstone, Isle of Bressay, Shetland Islands, UK Devonian age
Red sandstone			Red Navajo sandstone in Antelope Canyon, Arizona, USA. Red colour due to hematite iron cement Triassic/ Jurassic age
Mudstone			Permian red mudstone with paler siltstone beds, Bassin de Lodève, Hérault, la Lieude, Mérifons, France

Table 4.5. Common sedimentary rocks, continued

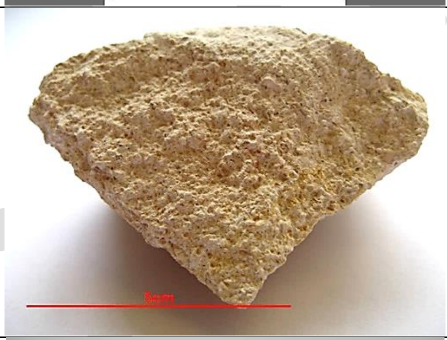
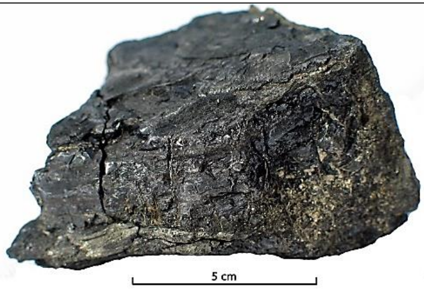
Sedimentary rock	Images		Source of exposure image
	Specimen	Exposure	
Shale	 5 cm		Marine shale, Slate Hill Road, Marcellus, New York, USA Devonian age
Clay	 5 cm		Clay, Estonia Quaternary age
Fossiliferous limestone	 5 cm		Fossil-iferous limestone of the Green Bridge of Wales arch and stack, Pembrokes hire, Wales Carbonifero us age
Oolitic limestone			Oolitic Jura limestone in Rothenstein III quarry, Jura region, France Jurassic age
Chalk	 5 cm		The high chalk cliff of Møn, Denmark Cretaceous age

Table 4.5. Common sedimentary rocks, continued

Sedimentary rock	Images		Source of exposure image
	Specimen	Exposure	
Rock salt			Colonel salt cave, Israel. Natural exposures of salt are only found underground, since salt dissolves in water
Coal			Dipping coal seam with an old mine entrance, Stellarton Formation, Nova Scotia, Canada Carboniferous age

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

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

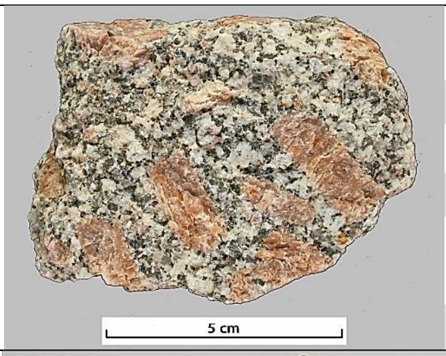
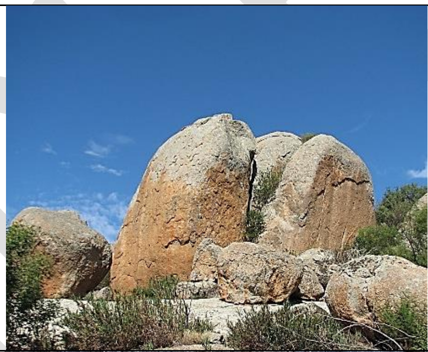
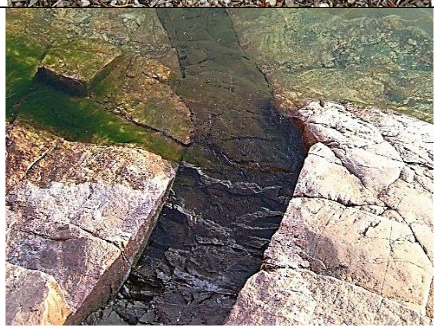
Igneous rock	**Image**		**Source of exposure image**
	Specimen	**Exposure**	
Granite			Granite exposures, Mount Hope, Victoria, Australia Devonian age
Gabbro			Gabbro from the Ukraine in a geological wall in the Botanical Folk Park, Blankenfelde Pankow, Berlin, Germany
Dolerite			Dolerite dyke on the edge of a river, Agwa Rock, Lake Superior Provincial Park, Canada

Table 4.7. Common igneous rocks, continued

Igneous rock	Image		Source of exposure image
	Specimen	Exposure	
Basalt			Basalt columns (formed as the basalt cooled) at the Giant's Causeway, Northern Ireland Tertiary age
Andesite			Andesitic lava flows, Stewart Peak volcano, Colorado, USA Tertiary age
Volcanic ash			Volcanic ash laid down as tuff layers in the Aeolian Islands near Sicily, Italy Quaternary age

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

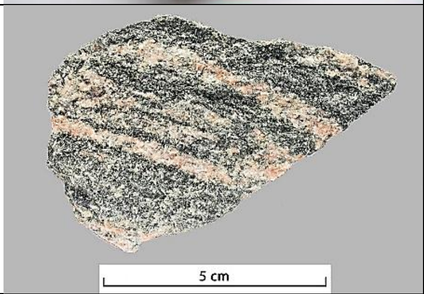
Mineral composition		Quartz and clay minerals in mudstone or shale	Quartz in sandstone	Calcite in limestone
Common regional metamorphic rock types – see Table 4.9				
Increase in heat and pressure ↓	Low-grade	Slate	Metaquartzite (or quartzite)	Marble
	Medium-grade	Schist		
	High-grade	Gneiss		
Common 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			Slate in a road cutting protected by rock anchors and wire mesh, Rothaar Mountains, North Rhine, Germany Devonian age

Table 4.9. Common metamorphic rocks, continued

Metamorphic rock	Images		Source of exposure image
	Specimen	Exposure	
Schist			Mica schist, La Pierre Blanche, island of Groix, Brittany, France Devonian age
Gneiss			The banded gneiss of Sugarloaf Mountain, Rio de Janiero, Brazil Precambrian age
Marble			Marble block in Carrara quarry, Italy – widely used as a building stone and for sculpting statues Jurassic age
Metaquartzite (quartzite)			Metaquartzite exposure, El Castellar, Zaragoza, Spain Ordovician 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.

Figure 4.4. Soil sequence in Altenberg, Germany

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.

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

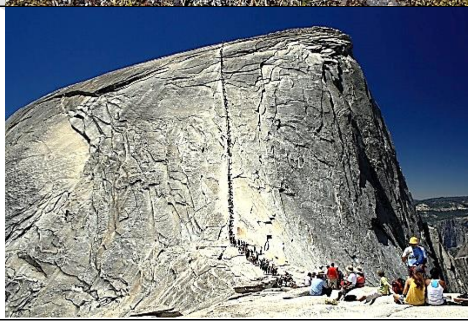
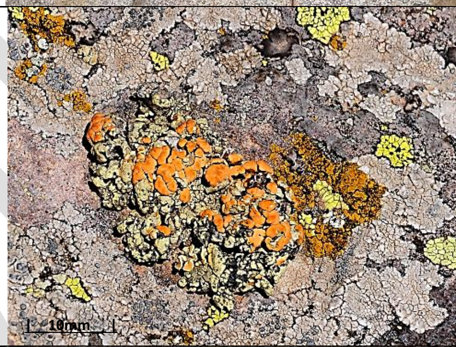
Process		Description	Image	Source
Physical	Freeze/ thaw	Water enters cracks, freezes, expands, then thaws and trickles deeper; as freeze/ thaw cycles continue, the crack is widened. Important where freezing/ thawing is common, as on mountain tops		Broken boulder, southern Iceland
	Heating /cooling	Rocks 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		Carbon-iferous limestone pavement with widened joints (grykes), Doolin Quay, Ireland
	Oxidation of sandstone and quartzite	Rainwater flows along joints, oxidising (rusting) iron minerals to bright yellow, brown and red colours		Chemical weathering along a joint in the Khondalite Rock formation at Rushikonda beach, Visakha-patnam,India
Biological	Lichens and mosses	Lichens are the first plants to colonise bare rock. Their tiny rootlets grow between the rock grains, weakening the rock as the lichen dries and contracts. They also have biochemical effects. Lichens are often followed by mosses, then soil		Lichens growing on bare rock, USA
	Soil-formation	The biological effects of weathering on bedrock produce soil		Soil layers in the Rhine Valley near Rastatt, Germany

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

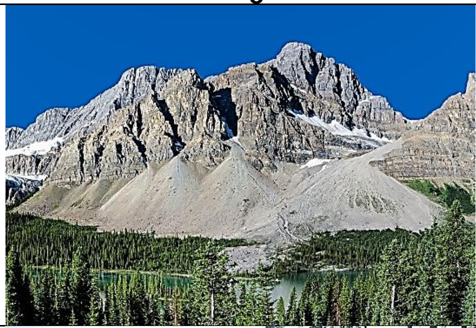
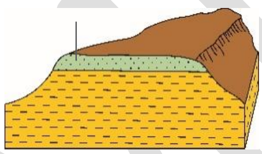
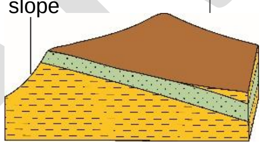
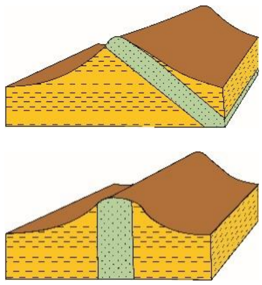
Process	Description	Image	Source
Gravity	Rock fragments, often weakened by weathering, fall off because of gravity. Large-scale rock-fall produces sloping screes which have cone-shapes under gullies. Erosion by gravity includes rock-fall and the sliding rocks of landslides		Scree cones, Bow Lake near Crowfoot Mountain, Alberta, Canada
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 river banks can fail catastrophically		Bank collapse due to undercutting by erosion, Tista River, Sundarganj Thana, Bangladesh
	Waves and the sediment they carry erode the foot of coastal cliffs, often causing rock-falls. These later become broken up by the waves		Beach closed by a coastal erosion rockfall, Oddicombe, Devon, England
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		A sand storm cloud blowing over Al Asad, Iraq
	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		Árbol de Piedra ('stone tree'), Eduardo Avaroa Andean Fauna National Reserve, Bolivia

Table 4.11. Important erosional processes, continued

Process	Description	Image	Source
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		Person on bedrock scratched by glacial movement, Gorner Glacier, Zermatt, Switzerland

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

Landform	Description	Drawing	Image	Source
Plateau	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)			Table Mountain plateau, Cape Town, South Africa
Cuesta	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)			Cuestas, near Abel Erasmus Pass, Limpopo Province, South Africa
Ridge	Ridges have steep slopes in two directions and form when resistant rocks dip steeply or are vertical			Ridge, Mount Rundle, near Banff, Alberta, Canada

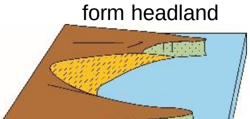
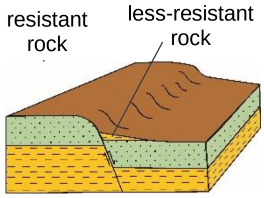
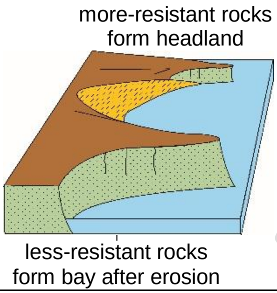
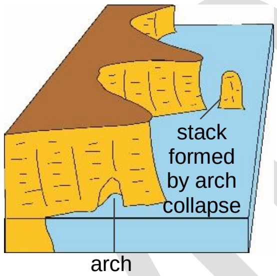
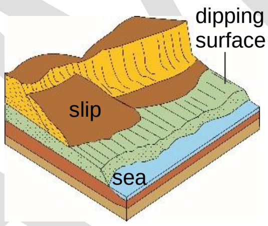


Table 4.12. Landforms formed by resistant rock layers, continued

Landform	Description	Drawing	Image	Source
Fault scarp	When the rocks on one side of a fault are more resistant than the other, a fault scarp often forms			Abert Rim fault scarp, Oregon – one of the highest in the USA
Headland and bay	When some coastal rocks are more resistant than others, headlands and bays form			A bay between headlands, Cabo de la Vela, Colombia
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			Steep cliffs and an arch, Island Archway, Great Ocean Road, Victoria, Australia
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, UK

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 river valley, Goriot, Pakistan
	by moving ice	Glaciers flowing down upland valleys erode both the sides and base of the valleys, producing U-shaped valleys		U-shaped glacial Prapic valley near Orcières, Hautes-Alpes, France
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 channels of the Zambezi floodplain in Namibia, seen from the air; airstrip lower right
	by water in lakes and seas	Rivers carrying sediment into lakes and quiet seas, deposit the sediments, building deltas which are often fan-shaped		Silvaplana delta building out into Silvaplana Lake, Switzerland
	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.		The Isunnguata Sermia glacier in the background deposited the moraine in the foreground, Kangerlussuaq, Greenland

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.

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		Bedded sandstones and siltstones, Quebrada das Conchas, Salta, Argentina
Lamination	Muds are also often laid down in layers, but these are much thinner layers called **laminations**		Laminated mudstone, Hesselberg, Germany; Lower Jurassic
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		Large-scale (wind-formed) cross-bedded sandstone, Angel's Landing Trail, Zion National Park, Utah, USA; wind from right

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-marked Cambrian sandstone, Wiśniówka Duża, Poland; water flow direction from top to bottom of the bedding plane
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-marked fine sandstone, Sierras Bayas, Olavarria, Argentina. The wave crests moved from top right to bottom left
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 (mudcracks)	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 around a dinosaur footprint in mudstone, Loulle, Franche-Compte, France

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.

4.1.2.3. Igneous processes

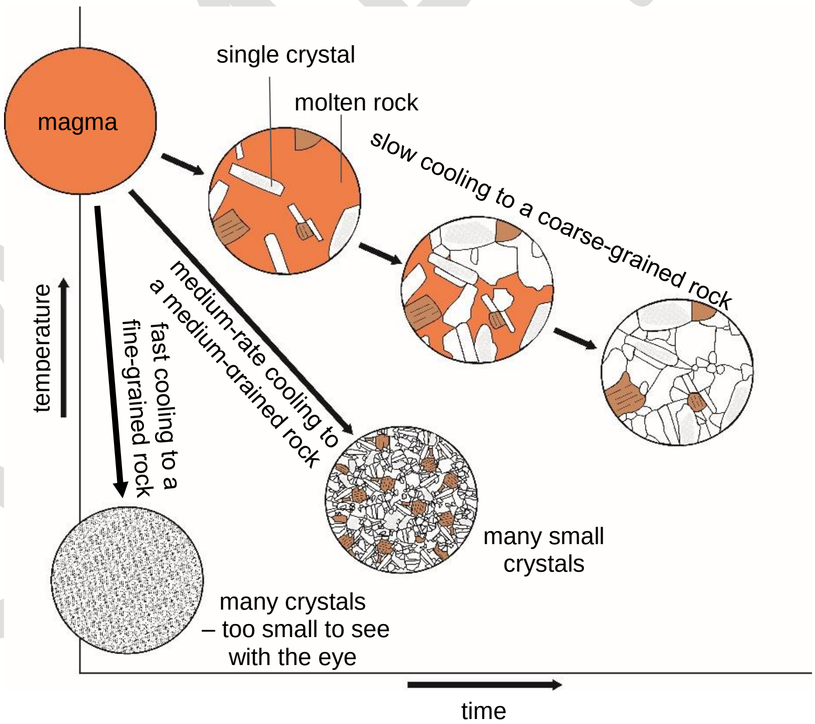
When rocks become hot enough, they melt. Since rocks are usually a mixture of minerals, they often do not melt entirely but only partially melt, with the lowest-melting point minerals melting first. If the magma produced by **partial melting** flows away, it has a different chemical composition from 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.

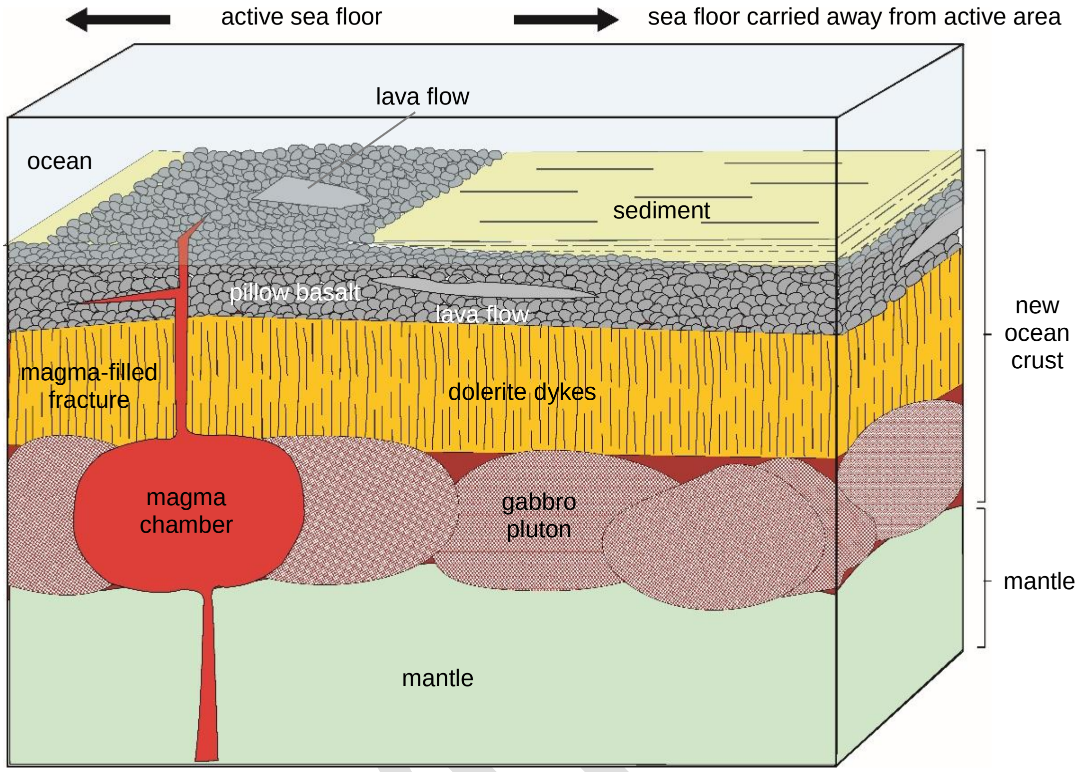
Rising magmas may stop deep underground, cool down and crystallise in **magma chambers**. The magma has plenty of time to cool and for crystals to grow in the cooling melt. The result is a coarse-grained igneous rock. If the magma rises higher it becomes cooler and so crystallises more quickly into medium-grained 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

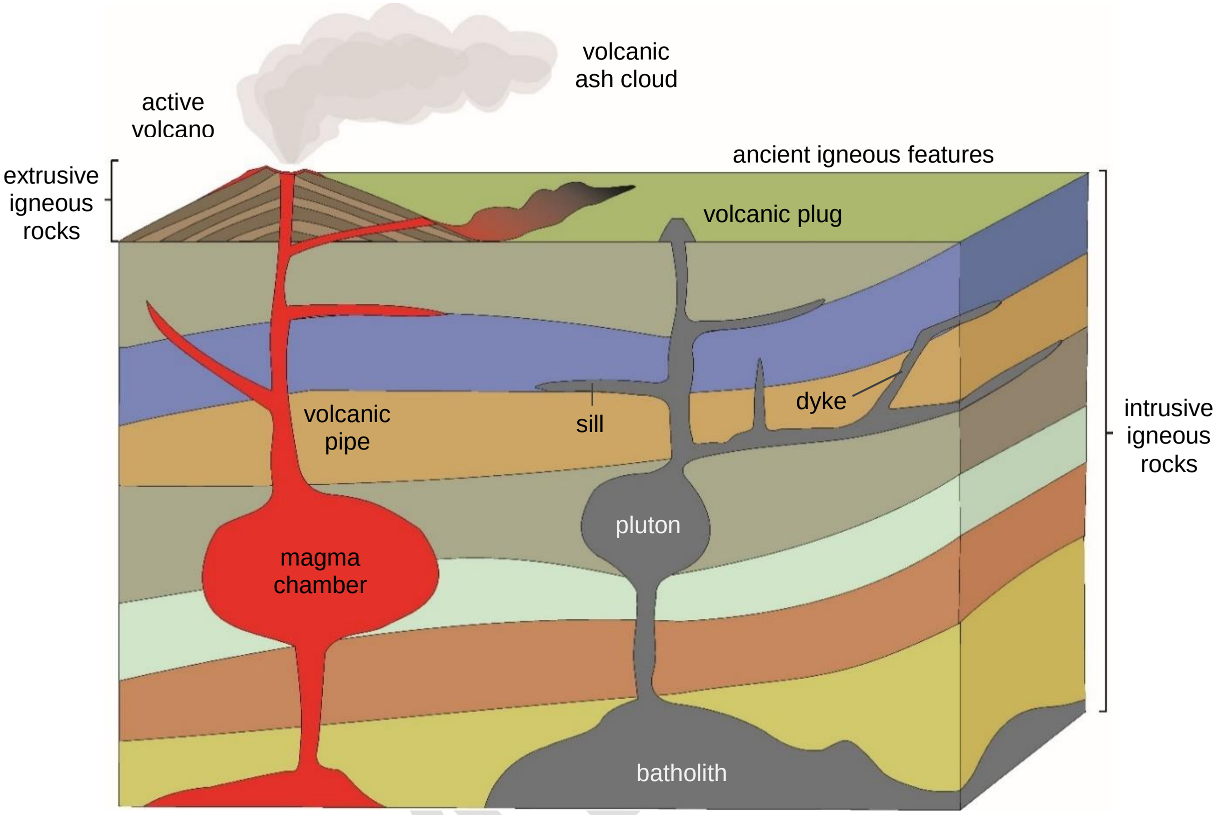
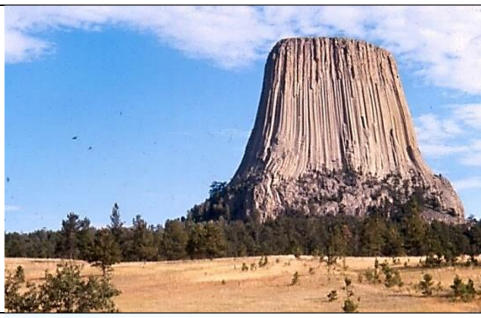


Table 4.15. Important igneous features

Igneous feature		Description	Image	Source
Pillow lava	Modern	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	When ancient pillows break in half, the finer-grained basalt of the margins can often be seen. Since later pillows sink down between earlier pillows as they are formed, their shapes can be used to tell whether a sequence has been turned upside down (inverted)		Inverted Ordovician pillow basalts, Crozon, Brittany, France

Table 4.15. Important igneous features, continued

<table>
<tr><th>Igneous feature</th><th colspan="2">Description</th><th>Image</th><th>Source</th></tr>
<tr><td>Volcanic plug</td><td colspan="2">Volcanic plugs are the remains of feeder pipes of the volcanoes that used to be above. The rest of the volcano has been eroded away, but the resistant central volcanic rocks remain</td><td></td><td>The Devil’s Tower volcanic plug in Wyoming, USA, famous due to the film ‘Close Encounters of the Third Kind’</td></tr>
<tr><td>Sill</td><td>Magmas intruding along sedimentary or volcanic layers (bedding planes) cool and crystallise, forming sills</td><td rowspan="2">Most sills and dykes are medium-grained and some have chilled (finer-grained) margins. Some meta-morphose the rocks they intrude, producing baked margins</td><td></td><td>Kilt rock sill, Skye, UK; the overlying layers have been eroded away</td></tr>
<tr><td>Dyke</td><td>Dykes form when magmas fill fractures in rocks, and then cool and crystallise</td><td></td><td>Dark dolerite Precambrian dykes (1100Ma), cutting through paler 1800Ma rocks, Koster Islands, Sweden</td></tr>
<tr><td>Pluton/ batholith</td><td colspan="2">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</td><td></td><td>Satellite image of the 30km-wide Brandberg Massif granite intrusion in Namibia, that baked the surrounding rocks into a dark metamorphic aureole</td></tr>
</table>

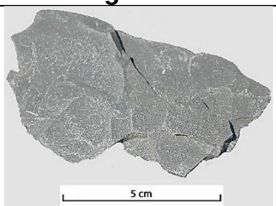
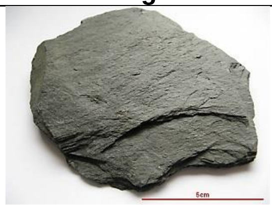
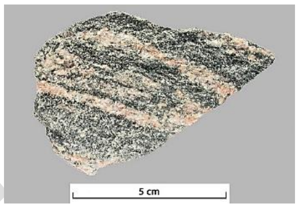
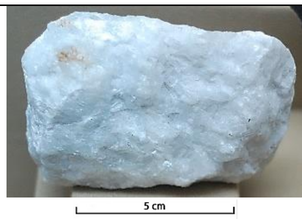
Igneous processes form part of the internal rock cycle, the part of the rock cycle driven by energy from the Earth. We have known how igneous rock cycle processes operated for many years, but their underlying causes have only been understood more recently, through plate tectonic theory, as in Table 4.21.

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.

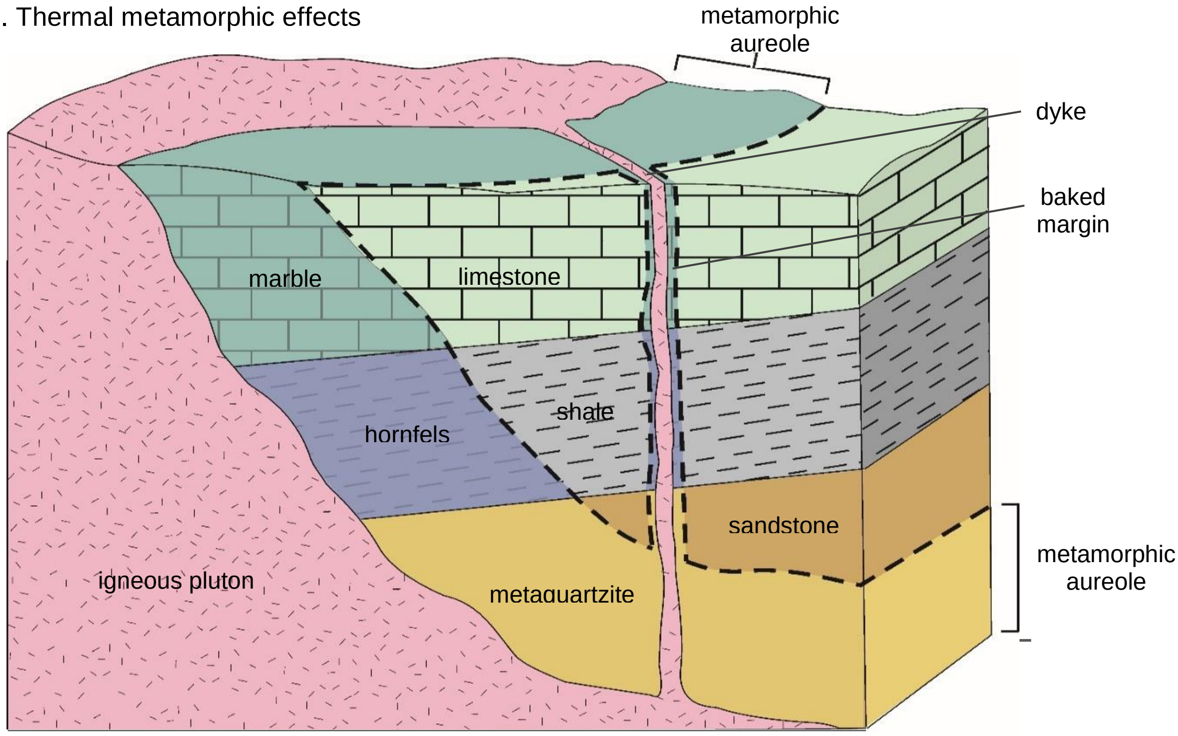
Regional metamorphism, caused by plate collision, produces rocks ranging from low-grade slates to high grade gneisses, together with marbles and metaquartzites, as shown in Table 4.16. These resistant rocks are usually impermeable and tend to form higher land and fairly rugged landscapes.

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).

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 15km, 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.

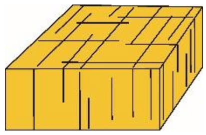
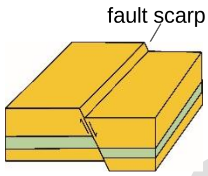
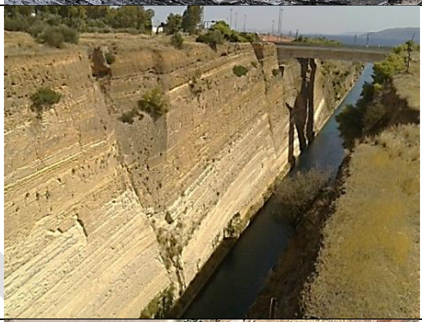
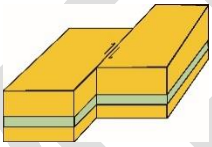
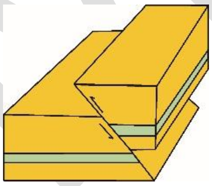
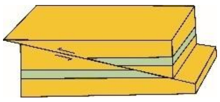
Rocks are also deformed when plates move apart or move past one another but, because temperatures are relatively low, they usually fracture rather than behaving plastically.

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 45^o. Under very intensive compression, fault planes usually have lower angles of around 10^o 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			Jointed siltstone bed in Ordovician shale, Fort Plain, New York, USA
Normal fault		Under tension, one block has slid down the fault plane relative to the other – usually steep, 60º or more			Normal faulting in the walls of the Corinth Canal, Greece
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 – usually on fault planes of around 45º			Reverse fault in sandstone, Oregon, USA
Thrust fault		Under great compression one block has been forced over another – on a shallow fault plane of around 10º			Right hand block thrust up over left hand block, Lilstock Bay, Somerset, UK

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	An upfold – this anticline is an open fold with a rounded hinge		An anticline in Precambrian gneiss along NJ Route 23 near Butley, New Jersey, USA – person for scale
Syncline	A downfolded syncline – an open fold with a fairly angular hinge		A syncline in the Neogene Barstow Formation sandstones, San Bernardino County, California, USA
Open fold	Open folds, with an angle between the limbs of more than 45º, together with rounded hinges		Folded bedded limestone in the Glasen-bachklamm Gorge, Austria

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 near Ágios Pávlos in southern Crete
		Tight fold with a rounded hinge		Folded 2.6-billion-year-old Precambrian banded iron formation, near Soudan, Minnesota, USA
Isoclinal fold	Folds with parallel limbs			Small isoclinal fold in the Monts d'Arrée near Commana, France

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