Six Common Kinds of Rock from Ireland

Fully revised and illustrated second edition

Ian Sanders

Published by the Department of Geology, Trinity College Dublin,

to mark the International Year of Planet Earth, 2008

planetearth®
Earth Sciences for Society

Preface and Acknowledgements

These notes and accompanying rock samples are a teaching resource supplied free of charge to primary and secondary schools throughout Ireland. The notes aim to give plain facts and explanations for teachers wishing to understand more about rocks, whether they are teaching classes in the examination years of secondary school, or in the early years of primary education. The notes also cover the geology component of Core Unit 1 in the new (2004) syllabus for the Leaving Certificate Examination in Geography.

Please pass the samples around the class and handle them. If they get grubby with use, they will respond to gentle scrubbing in warm soapy water!

To obtain further copies of this booklet and to ask for extra rock samples visit: www.tcd.ie/geology/outreach/

Students and staff at the Department of Geology in Trinity College who prepared the rock samples (more than 60,000 pieces in total) are grateful to the following people for their kind permission to collect material:

Alan French of Hill Street Quarries, Arigna, County Leitrim,
Eddie Power of Ormonde Brick Ltd, Castlecomer, County Kilkenny,
Luis Grijalva of Whelan's Limestone Quarries, Ennis, County Clare,
Gary Flaherty of Whitemountain Quarry, Lisburn, County Antrim,
Colm Walsh of Walsh's Granite Quarry, Stepaside, County Dublin.

Photograph credits: Peter Coxon (Figs 10, 21), George Sevastopulo (Figs 7, 19), John Graham (Figs 6, 8) and Juan Carlos (Fig. 9).

The project has the support of the Royal Irish Academy's Geoscience Committee. It was part funded through a Griffith Geoscience Research Award, grant-aided by the Department of Communications, Energy and Natural Resources under the Strategy for Science, Technology and Innovation 2006 to 2013 and the National Geoscience Programme 2007-2013. The views expressed in this study are the author's own and do not necessarily reflect the views and opinions of the Minister for Communications, Energy and Natural Resources. A donation from Quinn Group is gratefully acknowledged.

Revised second edition published 2007 by the Department of Geology, Trinity College, Dublin

ISBN 0 9521066 6 3

Contents

Prelude: the Great Sugar Loaf Myth

1 Introduction
- 1.1 Where not to begin 4
- 1.2 Handling and storing the rock samples 4
- 1.3 Looking at rock in the open: finding exposed bedrock 5
- 1.4 The Ice Age and the source of the sand and clay 6

2 The six kinds of rock: their sources, uses and descriptions 8
sandstone; mudstone; limestone; basalt; granite; schist

3 How were the six kinds of rock made?
- 3.1 Sandstone, mudstone and limestone – sedimentary rocks 11
  sandstone; mudstone; limestone;
  sedimentary rocks in general; sedimentary layers
- 3.2 Basalt and granite – igneous rocks 16
  basalt; granite; igneous rocks in general;
  the chemical composition of magma;
  the mantle and continental crust as magma sources
- 3.3 Schist and metamorphic rocks 22
  schist; metamorphic rocks in general;
  metamorphism and mountain building
- 3.4 Partial melting and the rock cycle 24

4 Geological time 26

5 The geology of Ireland
- 5.1 The geological map of Ireland 27
- 5.2 Ireland's geological history 28

6 Further interesting things about rocks
- 6.1 Life in tropical Carboniferous seas 31
- 6.2 Making Ireland's mountains by erosion 32
- 6.3 Water, oil and gas in porous sandstone 34
- 6.4 Formation of zinc and lead ore in Ireland 36
- 6.5 How is the age of granite measured? 37
- 6.6 How can liquid basalt come out of solid mantle? 39

7 The unifying mechanism: plate tectonics 41
tectonics; where plates are moving apart;
where plates converge; subsidence and uplift

8 Ideas for class work 46

9 Further information and reading 47

10 Index of technical terms 48

Prelude: the Great Sugar Loaf Myth

Some twenty five years ago my daughter showed me a picture in her junior school text book of the familiar cone-shaped summit of the Great Sugar Loaf Mountain in County Wicklow. She was fascinated to learn from the picture's caption that the mountain had once, long ago, been an active volcano.

The mountain, however, was never a volcano: it acquired its distinctive shape through erosion. The rock from which it is made is particularly hard sandstone. The surrounding rocks are softer, and over a long period of time they have been worn away leaving the more resistant sandstone to stick out as a sharp peak.

Today the romantic, though erroneous, idea of ash and red hot lava spewing forth over the gentle Wicklow countryside lives on. The myth is not easily dispelled. It survives, perhaps, because of a natural fascination with the prehistoric past and with the fiery violence of volcanoes.

In providing this booklet and accompanying rock samples I aim to explain just how Ireland's ancient landscape evolved, and how the underlying rocks were made. Handling actual pieces of rock will, I hope, make the explanations more tangible, and reinforce the truth that the rocks are incredibly old, that they have been deeply buried, and that some of them *did*, after all, come from volcanoes.

Geology, the study of rocks, is more important today than it has ever been. The year 2008 has been designated International Year of Planet Earth (IYPE) by the United Nations General Assembly, meeting in New York. The urgent aim of IYPE is to foster a global understanding of geology, so that we may all become more keenly aware of what we can do, and what we cannot do, with the materials of the Earth – fuel, water, metals – if we are to preserve our planet for future generations.

Ian Sanders

September 2007

The Great Sugar Loaf Mountain in County Wicklow, pictured above, is not an extinct volcano, as its cone-shaped appearance might suggest. It has a prominent peak because it is made from a huge block of hard sandstone surrounded by softer rocks. Over a very long period of time, erosion has selectively removed the softer rocks, leaving the hard sandstone standing proud. Many other mountain peaks in Ireland have a similar origin to the Great Sugar Loaf. Among these are Errigal in County Donegal, Croagh Patrick in County Mayo, the Twelve Bens in Connemara, and the Kerry Mountains.

1 Introduction

1.1 Where not to begin

Geography books at school often begin the section on rocks with the theory of *plate tectonics*. But to start there is probably *not* the best way to get to understand geology. It is perhaps better to begin by just looking at rocks and becoming familiar with their characteristics and their uses. After this, it should be much easier, and more interesting too, to learn about how rocks were formed, how old they are, and what they tell us about the changing pattern of land and sea over the great expanse of geological time. Only then, after getting a basic feeling for what rocks are about, does the elegance of the plate tectonic theory – which weaves together so many different strands of geology – come into its own. The plate tectonic theory is the 'Summary and Conclusions' section of the story, not the introduction. To kick off with plate tectonics is rather like being told the ending to a good novel – it spoils the fun of seeing the plot unfold.

1.2 Handling and storing the rock samples

Two pieces of each kind of rock are included in the set. (Additional pieces will be supplied on request, for the cost of postage, for as long as stocks remain; visit the website, www.tcd.ie/geology/outreach/ for details). The rock samples should be passed around and handled by every member of the class. To avoid confusion, each piece has been spotted with coloured paint, as follows:

Sandstone	yellow
Mudstone	lilac
Limestone	blue
Basalt	green
Granite	red
Schist	orange

Before using the rock samples for the first time, check them for sharp, jagged edges. These should be rubbed smooth against a rough surface, such as a concrete block, to avoid minor cuts and to protect the plastic storage bag.

Although the rocks are hard, they will become bruised and dusty if they are allowed to bang against each other. The mudstone samples are most vulnerable and have been packed in a small bag of their own to help preserve them. You might consider storing the rocks in a rigid container such as a biscuit tin or lunch box, or perhaps a specially made wooden tray divided into labelled sections. If the specimens become dirty or greasy from continued handling, they may be cleaned by brushing them in warm soapy water and drying them off with a soft cloth or paper tissues.

1.3 Looking at rocks in the open: finding exposed bedrock

Handling rock samples is a good way to start, but it is even better to get out into the open air and look at rocks 'in the field'. Where do rocks occur? Believe it or not, wherever you go in Ireland you are never far away from solid rock, but you rarely see it because it is usually just below the surface. The next time you pass a large, freshly dug hole in the ground, take a closer look. You will probably notice that the hole goes down into brownish sand and clay, perhaps with stones in it. This material is usually several metres thick, and below it, if the hole is deep enough, you will see solid hard rock, which is called *bedrock* (Figure 1).

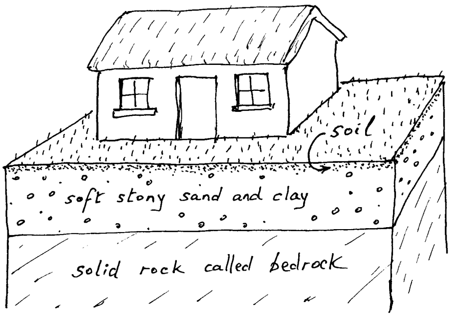


Figure 1 Block diagram showing what lies under the ground. A layer of soft sandy clay with stones, a few metres thick, usually covers hard rock, called bedrock.

In some places, nature has kindly saved us from having to dig a hole if we want to see solid rock. On rocky shores and in cliffs along the coast, breaking storm waves have removed the soft sand and clay and cut into the bedrock (see Figures 2 and 3). Bedrock that is uncovered and visible is said to be *exposed*. On high ground and mountain tops, loose soil has usually been eroded by frost, wind and rain and the bedrock sticks through. Similarly, bedrock is exposed in the banks and beds of rivers, particularly in gorges and at waterfalls. These are all suitable places to look at rock for yourself, provided of course that you take reasonable care. Remember that rocky shores can be very slippery below the high water mark, that freak waves can wash you into the sea, and that a rising tide may cut off your retreat. You should take particular care on steep ground, on paths along the tops of cliffs, and at the foot of a cliff or steep slope where loose material may fall on you. A number of well tried and tested places to visit are listed on the Trinity College website: www.tcd.ie/geology/outreach

In quarries and road cuttings it is not nature, but heavy earth-moving machinery, that has stripped the covering sand and clay, and left the bedrock exposed. Five of the six kinds of rock described in this booklet (all but the schist) were collected from quarries. The rocks are extracted as raw materials for the construction of roads and buildings. Quarrying is a multi-billion euro business that plays a key role in the Irish economy. Unfortunately, the use of explosives and heavy machinery make quarries dangerous places to enter, and permission to visit them will only rarely be given by the owner. Many road-side exposures of rock are also dangerous to stop at, because of fast-moving traffic.

1.4 The Ice Age and the source of the sand and clay

The stony sand and clay that hides the bedrock in many parts of Ireland has an interesting origin. It is linked to a period in the past, before about 10,000 years ago (based on carbon-14 dates), when the climate was extremely cold. During this period the land was buried for much of the time beneath a thick sheet of ice, rather like Greenland is today. It would have been far too cold to live here. This period of icy climatic conditions is known as the *Ice Age*.

The ice sheet was not stationary, but moved very slowly, spreading outwards under the huge weight of the snow that fell on it. The ice scraped and plucked the solid bedrock as it edged its way relentlessly forwards, and it became very dirty with all the sand, mud and broken stones that got carried along within it.

About 10,000 years ago, following many thousands of years of bitterly cold weather, the climate improved and the temperature rose. When the ice sheet melted, the debris embedded within it was left stranded, and became draped in a blanket of sandy clay with stones across the country. These loose materials are described as *glacial deposits* because they were dropped by melting ice.

Figure 2 A layer of stony sand and clay about three metres thick with hard, pale-coloured bedrock below it, seen in a cliff at Sutton, Dublin. The sand, clay and stones were originally trapped in dirty ice that melted a little over 10,000 years ago. They are described as *glacial deposits*. It is unclear why the upper part of the cliff is stonier than the lower part. The bedrock is made of sandstone.

In many cliffs around the coast thick glacial deposits can be seen resting on the bedrock (e.g. Figure 2). In places where the glacial deposits have been removed it is sometimes possible to see parallel scratches and grooves that were gouged into the solid bedrock by chunks of stone embedded in the base of the slowly moving ice sheet (Figure 3). In some places the glacial deposits make up the entire height of the cliff because the bedrock is below sea-level.

Figure 3 Parallel grooves on the surface of bedrock from which pebbly sand and clay were recently washed away by storm waves near Sutton Dinghy Club, Dublin. The grooves were carved by blocks of stone embedded in the base of an ice sheet that was moving slowly over the bedrock during the Ice Age. Keys and pocket diary give a scale.

Solid bedrock turns out to be extremely old – very much older than the glacial deposits. Its age runs to many *millions* of years.

You will learn in Section 4 how this vast expanse of time is divided into eras and periods with names such as ‘Carboniferous’ and ‘Cainozoic’. In Section 5 you will learn how ‘Ireland’ has changed through time, and in Section 6 (under subheading 6.5) you will learn how the precise age of a rock, in millions of years, can be measured.

But first, in Section 2, the six kinds of rock will be introduced and in Section 3 their origins will be explored.

2 The six kinds of rock: their sources, uses and descriptions

The sources of the rock samples are marked on the simplified geological map of Ireland on the back cover of the booklet.

Sandstone (yellow paint spot).
The sandstone comes from a large quarry operated by Hill Street Quarries Ltd near the flat top of Arigna Mountain in County Leitrim. The crushed rock is used beneath railway tracks, and it is retailed as Glenview Gold aggregate for patios and driveways. When finely crushed it is sold as play-sand.

As well as sandstone, Arigna Mountain contains several poor quality coal seams which were mined until 1990. Part of the mine was re-opened in 2003 as a heritage site and is a popular tourist attraction.

The sandstone samples are pale creamy brown, the colour of sand on the beach. Sandstone breaks into knobbly chunks that are hard. If you try scraping a piece with the tip of a pen-knife blade you will make no impression – it is harder than steel.

Mudstone (lilac paint spot).
The mudstone comes from a large open pit near the town of Castlecomer in County Kilkenny. It is used by Ormonde Brick Ltd to make bricks. The rock is first crushed and dampened with water to make stiff clay which is then pressed into the shape of bricks and fired in a large kiln. Castlecomer, like Arigna, was once a coal mining district. The last mine closed in the 1980s. You can find out more about the coal at the Castlecomer Discovery Park.

The mudstone is grey – the colour of mud – and if it is made wet and rubbed, it will feel slimy as the rock is being turned into mud. It breaks into smooth pieces with rather flat shapes, and it can be scratched very easily.

Limestone (blue paint spot).
The limestone is from Whelan's Quarry near the town of Ennis in County Clare. Similar limestone to this forms the bare hills of the nearby Burren district of County Clare. The quarried limestone is crushed and used in foundations, and is also used as aggregate (small stones) in concrete.

Limestone is mixed with mudstone to make cement. The mixture is crushed and roasted in a kiln to produce cement clinker which is then ground down to fine grey cement powder. If limestone is heated on its own in a kiln it is converted to *lime*. Lime is a caustic white powder (calcium oxide) that is used for making mortar and was once used widely as whitewash on cottages.

The limestone is pale grey, and breaks into chunky pieces. It can be scratched with the tip of a pen-knife blade, but it is harder than the mudstone. A distinctive feature of limestone is that it fizzes very slightly if a drop of a weak acid like vinegar is placed on it. You may need to scrape and powder the limestone surface a bit first, and use a magnifying glass to see this effect. The fizzing is due to the production of tiny bubbles of carbon dioxide gas. Dilute hydrochloric acid works much better than vinegar, but this acid is more difficult to obtain. The chemical reaction between limestone and hydrochloric acid is written:

$$CaCO_3 + 2HCl = CaCl_2 + H_2O + CO_2 \text{ (gas)}$$

limestone + acid = calcium chloride + water + carbon dioxide

Basalt (green paint spot).
The basalt is from Whitemountain Quarry which is on the hill north of the town of Lisburn in County Antrim. Basalt is the bedrock over much of County Antrim and extends to the north coast where the famous Giant's Causeway is made from spectacular columns of basalt. Quarried basalt is used in foundations for roads and buildings.

Basalt looks a bit like limestone because it breaks into knobbly grey pieces. However, it is harder than limestone, and darker in colour. Unlike limestone, neither vinegar nor hydrochloric acid will fizz when dripped onto its surface.

Granite (red paint spot).

The granite is from Walsh's Quarry on the eastern slopes of Three Rock Mountain in south County Dublin from where there are magnificent views over Dublin Bay. Large blocks of granite are prised whole from the face of the quarry by hammering wedges into closely spaced drill holes, and without use of explosives. The blocks are then sliced with a huge diamond-tipped circular saw into slabs, or cut into blocks that are carved by a stone mason.

Granite slabs cover the walls and floors of many public buildings, and polished granite slabs are increasingly used as kitchen work-tops.

Granite is a light-coloured, speckled rock with a distinctive gritty appearance. Look carefully and see if you can spot four different kinds of component particle. The most abundant kind is milky white to pale cream, it may break along flat surfaces, and is called *feldspar* (pronounced *fell*-spar). The grey to glassy kind that always breaks unevenly is called *quartz*. The conspicuous clear shiny flat sheets are called *mica* (pronounced *my*-ka). The mica can be split into transparent flakes like fish scales with the tip of a pen-knife blade. Small dark brown or black flakes are a different kind of mica. The separate kinds of component – feldspar, quartz and the two kinds of mica – are called *minerals*. All rocks are made from minerals, but it is only possible to see them clearly in rocks, like granite, where the grains are quite large.

Schist (orange paint spot).

The schist was collected from either Glendalough or Glenmalure in County Wicklow. Glendalough is the site of an Early Christian monastic settlement in a scenic, steep-sided, flat-bottomed (U-shaped) valley with lakes. The valley's shape suggests that it was carved by a glacier during the Ice Age. Glenmalure is the next valley to the south. Loose blocks of schist were gathered and broken up using geological hammers.

Schist splits into flat pieces with a wavy surface and silky sheen. Its colour is silvery grey or golden brown. If it is scraped, tiny flakes of shiny mica fall off.

3 How were the six kinds of rock made?

3.1 Sandstone, mudstone and limestone – sedimentary rocks

Sandstone, as its name implies, is sand that has turned into stone. Its origin is illustrated in Figure 4. Sand grains are eroded from older rocks, flushed by rivers into the sea, and settle on the seabed. In some places the seabed continues slowly and steadily to go down, or *subside*, so that, given enough time, great thicknesses of sand accumulate, layer by layer. The older, more deeply buried layers become compressed by the weight of the younger layers that cover them over. The deeply buried layers also get warm because the temperature rises as you go down into the Earth. In Ireland, for example, it rises by 20°C per kilometre. The temperature at the surface (strictly, one metre beneath the surface) is usually steady at 10°C, so two kilometres down it will be about 50°C (Figure 5). Warmth, and the pressure due to burial, cause the damp grains of sand to bond together strongly to make hard sandstone. If you look carefully at the sample it is just about possible to pick out some of the original grains of sand. The change from sand to sandstone is a bit like the way sugar goes hard after getting damp. The hardening process is called *lithification* (pronounced lith-if-i-*kay*-shun: it means turning into stone, from the Greek word *lithos* = stone).

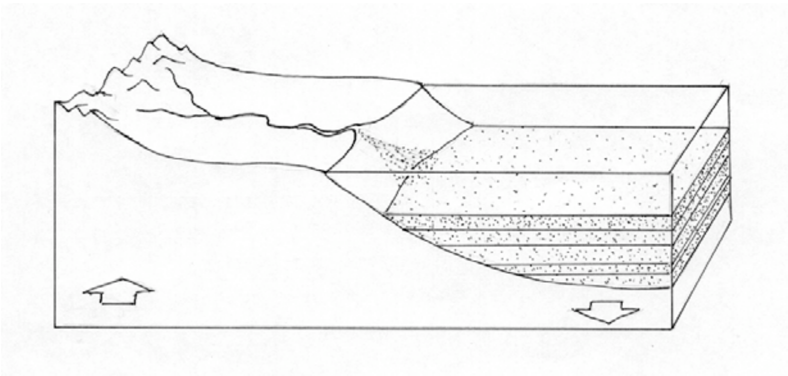


Figure 4 Block cut-away diagram showing how sandstone is made. Sand is transported by rivers from mountains to the sea, and a thick accumulation of sand builds up as layers on the seabed which is slowly subsiding. The deeply buried layers are warm, moist and compacted. Here the sand grains stick together to make hard sandstone in much the same way as damp sugar goes hard.

The sandstone from Arigna is made from sand that was washed into the sea by rivers about 310 million years ago. This was during a time that geologists call the Carboniferous Period which lasted 60 million years. (Geological time will be explained in Section 4.) At that time, most of Ireland lay submerged beneath the waves and was steadily subsiding. The sand is thought to have come from a range of mountains that lay far to the north. These mountains were eroded to make the sand, and they no longer exist today.

Temperature below the Earth's surface in degrees C

Depth in kilometres beneath the surface

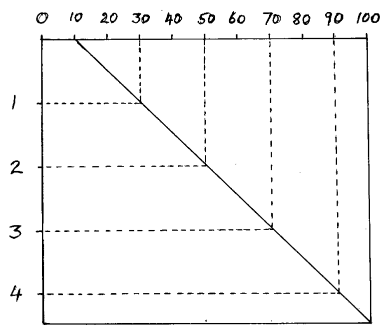


Figure 5 Graph showing how in Ireland the temperature of the ground gets hotter by 20°C for every kilometre you go down. The temperature at the surface is about 10°C, so 1 km down it will be 30°C, 2 km down it will be 50°C and so on. Anyone who has been down a deep mine will know about this. But does the temperature increase forever in this way? It probably does not, as we shall see in section 6.

The sandstone was collected from the top of Arigna Mountain, yet it was formed deep beneath the seabed. Therefore, after the sandstone had formed, subsidence went into reverse and the seabed eventually became dry land. First the upper layers of loose sand became removed by erosion, and in time the more deeply buried layers of hard sandstone became exposed at the Earth's surface. Possible causes of seabed subsidence and uplift are considered in Section 7.

Mudstone is mud that has changed into stone. It has a similar origin to sandstone. Muddy water flows into the sea and the mud particles, being tiny, settle out slowly. Mud builds up layer by layer into a great thickness on the subsiding seabed. The weight of the overlying layers squeezes the water from the warm deeply buried mud, turning it into mudstone and also flattening it so that it now splits horizontally. Mudstone that splits this way is often called *shale*.

The formation of mudstone at Castlecomer began, like the sandstone, about 310 million years ago during the Carboniferous Period when 'Ireland' was under the sea. The rivers from the north carried mud as well as sand into the sea, and in the Castlecomer area it was mud, rather than sand, that settled to the seabed.

The mudstone is now at the surface so, as with the sandstone, subsidence of the seabed eventually went into reverse. The seabed became dry land which was eroded, and the mudstone that was once deeply buried became exposed.

Limestone, like sandstone and mudstone, also originates by the settling of materials onto the subsiding seabed. In its case the materials are not grains of sand or tiny particles of mud but the shells of many different marine creatures. Shells are made of a substance called *calcium carbonate* whose chemical formula is written $CaCO_3$. The organisms make calcium carbonate by extracting dissolved calcium and carbon dioxide from the sea water, and combining them together in their living cells to grow their protective shells. Thick accumulations of calcium carbonate in shells and shell fragments build up as layers on the subsiding seabed, and become deeply buried and changed into hard rock.

The formation of the County Clare limestone began on the seabed about 340 million years ago, somewhat earlier than the sandstone and mudstone, but still during the Carboniferous Period. At that time very little sand or mud was being supplied by rivers and almost the only things settling out on the seabed were the calcium carbonate remains from dead creatures. Remains of corals, sea lilies, trilobites and various shell fish, as well as myriads of microscopic organisms, in this limestone tell us that the climate was tropical with abundant sea life.

As with the sandstone and mudstone, the seabed eventually stopped sinking and began to rise. With erosion the limestone, once deeply buried, ended up at the surface where we find it today.

Sedimentary rocks in general. Sandstone, mudstone and limestone are called *sedimentary* rocks because they are all made by the settling and accumulation of bits and pieces of material collectively known as *sediment*.

Sediment usually accumulates on the seabed as in the examples described above, but it can also accumulate in other places, such as the bed of a fresh-water lake or even on land (e.g. on the flood plain of a large river, or as sand dunes in a desert). The important thing is that sediment will only become hard sedimentary rock if the land surface or seabed continues to subside for a long time (usually millions of years) to allow a sufficient thickness of sediment to accumulate. Places where this subsidence is happening today (such as the bed of the North Sea), or happened in the past, are known as *sedimentary basins*.

Where does sediment come from? Sand grains and specks of mud are derived from the crumbling of older rocks that have been weathered. The particles are carried ‘downhill’ to a lower level by running water or sometimes by moving ice or by wind, before eventually coming to rest (usually on the seabed because this is the lowest level they can reach). The calcium used to make shells (and hence limestone) also comes from the weathering of older rocks, but in this case the calcium dissolves in rain water and is transported in solution by rivers to the sea. (Water with dissolved calcium is known as *hard water*, and it causes a coating of calcium carbonate, called fur, on the inside of a kettle.)

Sandstone, mudstone and limestone between them make up most of the sedimentary rocks on the planet, but other kinds are important too. *Coal* is a sedimentary rock made from accumulated plants. (Peat would turn to coal if it became deeply buried and warmed). *Conglomerate* is a sedimentary rock that resembles concrete because it is made from pebbles, like those you see on a stony beach. *Rock salt* is an unusual sedimentary rock made entirely of salt (sodium chloride) that is left behind when seawater dries up completely.

Sedimentary rocks can have a wide range of colours. Limestone and sandstone are white or cream if ‘pure’, but if they contain mud they are grey. Many rocks are red because they contain a red iron oxide mineral called *hematite*. Others are green because they contain the green mineral, *chlorite*. Mudstone is black if it contains a lot of carbon (from the remains of organic materials such as plants).

Sedimentary layers. Sedimentary rocks would not be seen today if it were not for uplift of the land surface and erosion. Examples of places where horizontal layers of sedimentary rock that were once deeply buried are now high above sea level are familiar to us all. Recall the many flat-lying layers, almost a mile thick in total, in the walls of the Grand Canyon. Nearer home, flat-lying layers can be seen on the faces of Ben Bulben in County Sligo, in the famous Cliffs of Moher in County Clare, and at Downpatrick Head in County Mayo (Figure 6).

Figure 6 Layers of sedimentary rock at Doonbristy, a sea stack off the north Mayo coast at Downpatrick Head, close to the Céide Fields. Such layers are known as *beds* or *strata*. Here they are made of sandstone, mudstone and limestone. The conspicuous pale grey bed close to the top of the sea stack, for example, is limestone. The original sediment accumulated on the seabed as horizontal layers, and these have remained horizontal during their uplift and erosion. The stack became separated from the mainland relatively recently since it has an ancient fort (not visible in the photo) on its grassy top.

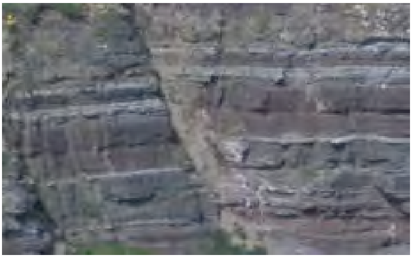
Geologists call layers of sedimentary rock *beds* or *strata*. Individual beds stand out because, during their accumulation, the supply of sediment changed from time to time, for example from sand to mud then back to sand, or perhaps because the supply stopped altogether for a while, and then later resumed.

Layers of sedimentary rock are not always horizontal. In many places they are inclined, either gently or steeply. Geologists describe them as *dipping* layers, and the angle of slope of a bed is called its *angle of dip*. For beds to be inclined they must have experienced more than simple subsidence and uplift. In some cases the layers have been buckled into arches and valleys, like giant sheets of corrugated roofing. Such crumpled layers are said to be *folded* (Figure 7). The tight bends are called *folds*. Bends, or folds, with the shape of a letter 'A' are called *anticlines*, and those shaped like a 'V' are called *synclines*.

Figure 7 Beds that have been buckled into giant corrugations in a cliff at Loughshinny in north County Dublin. The beds are said to be folded. They consist of limestone alternating with thin dark layers of mudstone, and are Carboniferous in age. You can count three A-shaped anticlines linked by two V-shaped synclines. Note the glacial deposits (sandy clay with stones) near the top of the cliff.

In some cases layers end abruptly where they come against a major crack, and continue on the other side of the crack at a higher or lower level than before (Figure 8). A crack like this is called a *fault.* The beds have moved relative to each other along the line (or, strictly, the plane) of the fault. Where the ends of the beds have rubbed against each other it is common to find crushed and broken rock fragments. This broken rock is called *breccia* (pronounced bretch-a).

Faults are thought to form in a sudden jolt when forces in the Earth build to breaking point. When a fault breaks it causes an earthquake.



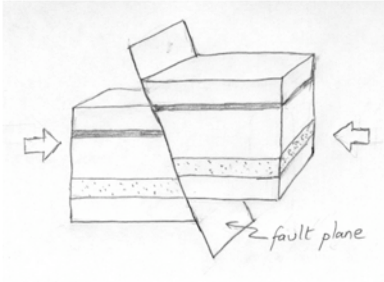


Figure 8   Part of a cliff face at Minnaun, west of Downpatrick Head, showing a *fault.* A fault is simply a large crack where the rock on one side has moved relative to the rock on the other side. The layers here have moved by about 3 metres. On the right is a diagram showing how the fault was caused by sideways forces.

3.2 Basalt and granite – igneous rocks

Basalt. We can see basalt being made today in places like Hawaii and Iceland. White-hot lava, as runny as water, wells up from below and pours out onto the surface where it cools quickly and hardens into black basalt (Figure 9). The high temperature of the lava (over 1100°C) means that it comes up from a very great

Figure 9 Glowing lava hardening into black basalt on the island of Hawaii.

depth, bearing in mind that the temperature under the ground normally increases by only about 20°C per kilometre. The lava comes from a region known as the *mantle*, deep within the Earth's interior.

Liquid basalt, incidentally, is called basalt *lava* only when it is on the Earth's surface. When it is below the ground, before it reaches the surface, its correct name is basalt *magma*. Basalt lava and basalt magma are otherwise the same.

Some people believe, quite wrongly, that the Earth's mantle is made of molten basalt, and that the magma simply leaks up cracks in the solid outer layer of the Earth to make volcanoes. The truth is that the mantle is solid. How we know this, and how it melts to make basalt will be explained in Section 6.6.

The basalt sample from County Antrim was formed about 60 million years ago, soon after the start of what geologists call the *Cainozoic Era* (Cainozoic and other names will be explained in Section 4). At that time enormous volumes of basalt lava poured onto the surface in what is now County Antrim. At the famous Giant's Causeway a 'lake' of basalt lava filled a shallow depression in the land. When the 'lake' cooled and hardened, the hot basalt contracted, and horizontal shrinkage led to the spectacular array of vertical basalt columns (Figure 10).

Figure 10 Columns of basalt at the Giant's Causeway on the north coast of County Antrim. Basalt lava poured onto the surface here sixty million years ago. A 'lake' of lava filled a shallow depression in the surface, and cracked into these polygonal columns when it hardened and contracted. Today on the foreshore we get a cut-away view through part of the original lava lake.

Sixty million years ago, when the Antrim basalt was erupting, Europe, Greenland and North America were all part of a single enormous continent. The Atlantic Ocean did not exist (Figure 11). However, forces deep inside the Earth were pulling the European and American parts of this ancient continent in opposite directions. It was stretched to breaking point and a huge crack developed from south to north. As the crack slowly widened, a chasm opened up and the sea flooded into it. The Atlantic Ocean was born. It has grown steadily wider since then, by about 2 cm per year. (This is roughly the speed that finger nails grow.) The origin of the Antrim basalt may perhaps be linked to that early stretching. Basalt lava continues to erupt at the centre of the widening Atlantic where the stretching still goes on today. Iceland's volcanoes are a part of this process.

Figure 11 Simplified map showing parts of Europe, Greenland and North America as they were 60 million years ago before the Atlantic Ocean existed. Red dots show places with basalt volcanoes. Everywhere was dry land or shallow sea.

Granite is formed, like basalt, when hot molten rock cools down and hardens. However, granite differs from basalt in two very important ways. Firstly it cools and hardens deep underground, not on the surface, and secondly it has a very different chemical composition from basalt, making it pale in colour.

Granite *magma*, rises from a great depth and is injected, or *intruded*, into an expanding cavity that resembles a huge subterranean 'blister', perhaps 10 or 20 kilometres wide. As the 'blister' inflates, its top surface bulges upwards and it also expands sideways (Figure 12). The 'blister' is called an *intrusion* of granite. It can also be called a *pluton* (pronounced ploot-on, after Pluto, the god of the underworld).

The cooling and hardening of granite magma is a bit like the freezing of water into ice. But whereas water freezes into just one kind of substance, i.e. ice, granite magma freezes into a mixture of several different kinds of solid material. These are called *minerals*, and as mentioned already in Section 2, each kind has its own name and appearance. *Quartz* is glassy grey, *feldspar* is creamy white, and the two kinds of *mica* are flaky sheets, large clear ones and small black ones, respectively. The minerals start off as small crystals in the cooling magma, and grow into large grains as the hot liquid slowly freezes. Geologists sometimes say that magma *crystallises* when it cools, instead of saying it hardens.

The sample of granite from County Dublin was formed 405 million years ago. (How we know its age is explained in Section 6.5). This was during a time known as the Devonian Period. Ireland was then above sea level, and below the ground in what are now counties Galway, Donegal, and Down as well as Dublin, Wicklow and Carlow granite magma was making huge 'blisters' or plutons. Granite is at the surface in these counties today, so at some stage the rock that originally formed the roofs to the plutons must have been stripped away by erosion (Figure 12, right hand side).

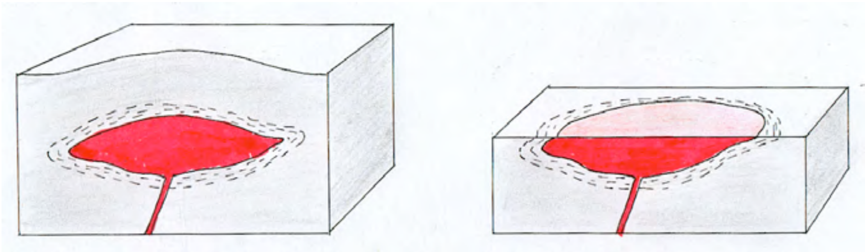


Figure 12 Block diagrams, each about 15 or 20 km wide, showing two steps in the formation of granite. On the left a cavity like a huge underground blister (called a pluton) has been inflated. On the right erosion has removed the rocks, perhaps a few kilometres thick, that were originally over the top of the pluton, and the granite is exposed at the surface. The zone marked with dashes shows where the rocks surrounding the granite pluton got very hot.

Igneous rocks in general Basalt and granite are examples of a major class of rock known as *igneous* rock (from the Latin *ignis*, meaning fire). Igneous rocks are made from lava or magma that cools down and hardens. They are clearly very different from the other major class of rocks, sedimentary rocks. Basalt and granite between them account for most of the igneous rock that exists.

When magma rises upwards from its source in the Earth's hot deep interior it usually does one of two things. It may reach the surface and pour out, usually through a volcano, to become a *volcanic* igneous rock (e.g. basalt), or it may stay underground and become a *plutonic* igneous rock (e.g. granite). Volcanic rocks cool rapidly and their mineral grains are tiny. In contrast, plutonic rocks cool slowly and have large, easily visible mineral grains.

Volcanic igneous rocks are also known as *extrusive* rocks, because the magma is extruded onto the surface (to become lava). On the other hand, plutonic igneous rocks are known as *intrusive* rocks because the magma is intruded (i.e. injected) into cavities that open up below the surface.

If basalt magma stays below the surface and forms a pluton, it will cool slowly and crystallise as a plutonic rock known as *gabbro* (Table 1). Gabbro has large mineral grains like granite, but they are dark in colour. If granite magma reaches the Earth's surface it cools rapidly and hardens into a smooth, light-coloured volcanic rock known as *rhyolite* (pronounced rye-o-lite).

Volcanic rock	Basalt	Rhyolite
Plutonic equivalent	Gabbro	Granite

Table 1 Correspondence between volcanic and plutonic rocks

Plutons often come in clusters. A cluster of plutons, touching each other, is called a *batholith* (from the Greek words *bathus* = deep, *lithos* = stone). An example of a batholith is the large area of granite in counties Dublin, Wicklow and Carlow which is made up of five separate plutons.

Magma cooling underground does not always make plutons. Sometimes it fills narrow vertical gaping cracks in the ground resulting in thin, sheet-like intrusions called *dykes*. Sometimes it is injected between adjacent beds of sedimentary rock, giving flat-lying or gently sloping sheet-like intrusions called *sills* (Figure 13). If dykes and sills are close to the surface, they cool down quite quickly, and their mineral grains are small like those in volcanic rocks.

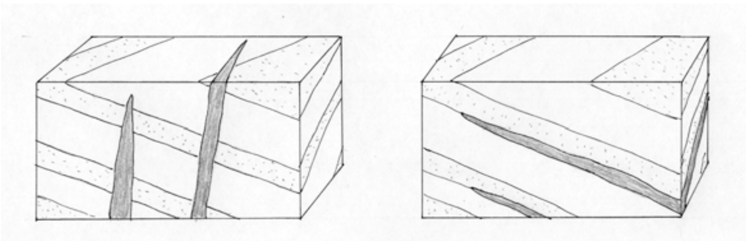


Figure 13 Block cross sections showing narrow sheet-like igneous intrusions in layered sedimentary rock. (A) Intrusions cutting across the layers are called *dykes*, while (B) intrusions parallel to the layers are called *sills*.

In some cases, instead of flowing out of a volcano as runny lava, magma explodes, causing a violent volcanic eruption. Volcanoes producing rhyolite (the volcanic equivalent of granite) often behave this way. Millions of tiny bits of frozen lava are launched into the air then fall back to the surface as *volcanic ash*. If volcanic ash later becomes turned into hard rock, would the rock be described as an igneous rock or a sedimentary rock? In fact it would be both, and the special name, *pyroclastic* rock, is sometimes used in such cases.

The chemical composition of magma. Minerals are really solid chemical compounds. Quartz is a compound called silicon dioxide or *silica*. It is made from the elements silicon (whose symbol is written Si) and oxygen (symbol O) in the proportions 1:2, and its formula is written SiO_2. Feldspar is a more complex chemical compound made from Si and O with aluminium (Al), sodium (Na), and potassium (K). Clear flaky mica contains Si, O, Al and K, while dark mica, contains, in addition, the elements iron (Fe) and magnesium (Mg).

Nearly all minerals in rocks contain Si and O, and are called *silicates*. In granite the total Si and O in all the minerals corresponds to about 70% by weight of SiO_2. Granite is therefore described as a silica-rich rock. (Note that the element, Si, is called silic***on***, and the oxide, SiO_2 is called silic***a***).

The chemical composition of basalt differs from that of granite in several ways. Basalt contains only about 50% by weight of silica, and is described as (relatively) silica-poor. The minerals in basalt contain a good deal of iron (Fe), magnesium (Mg) and calcium (Ca) as well as the usual Si and O. Minerals containing iron are generally dark in colour, hence basalt is a dark rock.

Some igneous rocks have a chemical composition roughly midway between granite and basalt, with about 60% by weight of silica. Such rocks are called *intermediate* igneous rocks, and they are well represented by the volcanic rock called *andesite*. Andesite is grey, and it gets its name from the Andes Mountains of South America where a great chain of volcanoes produce it.

The mantle and the continental crust as magma sources. It is thought that the difference between basalt magma and granite magma arises from a difference in where the two kinds of magma originate. Basalt magma, as mentioned above, is believed to come from a deep region of the Earth's hot interior known as the *mantle*. In contrast, granite magma is thought to come from a shallower region called the *continental crust*. The mantle and the continental crust are made from very different materials, as we will see, and when they start to melt, the magmas they produce are also very different.

The mantle is the 'middle' layer of the Earth. It makes up about 85% of the planet's volume. It lies below the continental crust and extends to a depth of about 3000 kilometres, which is roughly half-way to the centre. The mantle is thought to be made of a glassy-looking green rock called *peridotite*. We think this because bits of peridotite are sometimes carried up to the surface in basalt lava (Figure 14). We also think it because ordinary meteorites consist mostly of peridotite, and these 'rocks from space' are probably made of the same starting material as the Earth itself. Peridotite is made largely of oxides of Si, Fe and Mg, and it is a very *dense* rock i.e. a piece of it would feel heavy for its size.

The central part of the Earth, incidentally, below about 3000 km, makes up about 15% of the Earth's volume and is called the *core*. The core is thought to be made largely of molten iron metal.

Figure 14 A lump of the dense, green rock called peridotite. It is thought to be a piece of the Earth's mantle. It is about 10 cm wide and was brought to the surface in fast-flowing basalt magma. A skin of black basalt is still attached.

The continental crust forms the top layer of the Earth. It lies beneath the continents and their shallow shelf seas, but is absent beneath the deep oceans. It is made of familiar kinds of rock like sandstone, schist and granite. These are not as dense as peridotite, so the continental crust can be thought of as 'floating' on top of the mantle in the same way that oil, having a lower density than water, floats on water. The density of the continental crust averages about 2.8 grams per cubic centimetre (i.e. the rocks are about 2.8 times as heavy as water). The density of peridotite is close to 3.3 grams per cubic centimetre.

The continental crust is less than 1% of the Earth. It is mostly about 30 km thick, but is much thicker under mountain ranges (Figure 15). Its thickness has been measured by a technique called *seismology* which uses a device like a powerful echo sounder. The time taken for 'sound' to travel from the surface to the base of the crust and back again is measured carefully, and knowing the speed of sound through rock, the distance to the base of the crust can be worked out.

(The base of the continental crust is called the Mohorovicic discontinuity, or *Moho* for short. It is named after the Croatian scientist who discovered it in 1909.)

3.3 Schist and metamorphic rocks

Schist. How is schist made? This silvery or bronzy coloured, shiny flaky rock is produced in two stages. It begins as mudstone, and later the mudstone becomes converted to schist as a result of being intensely heated and squeezed. The heat makes new flakes of mica grow within the rock, and the squeezing process makes them line up parallel to each other. Each mica flake grows at right angles to the force which is squeezing and flattening the rock. With all the mica flakes lying parallel, schist can be split into flattish pieces which look shiny and wavy.

The schist sample from County Wicklow started out as a thick accumulation of mud on the seabed about 450 to 500 million years ago, during a time known as the Ordovician Period (pronounced order-*vish*-an). It was soon buried deeply and changed to mudstone. Later, 405 million years ago, the injection of granite magma into the mudstone formed a large pluton, as was explained in the last section on granite. The intense heat of the magma baked the mudstone in a zone around the pluton about one kilometre wide (marked by a dashed ornament on Figure 12). Also, when the magma was being injected it appears to have pushed against the mudstone, squeezing it flat as it was changed into schist.

Metamorphic rocks in general. Schist is an example of a class of rock known as *metamorphic* rock. Metamorphic rock is either igneous or sedimentary rock that has taken on a new appearance, usually as a result of becoming strongly heated and 'squeezed' within the Earth. The name comes from the Greek words *meta* = change and *morph* = form. Geologists say that an original rock (e.g. mudstone) is *metamorphosed* (e.g. into schist) during a process called *metamorph**ism***. The term metamor*phosis* is not used in geology.

Metamorphism leads to a wide variety of different rocks. As well as changing mudstone to schist, it changes limestone to *marble* (such as the famous green and white marble from Connemara) and it changes sandstone to hard *quartzite* (as in Errigal Mountain in Donegal and the Twelve Bens in Connemara). Mudstone is not always changed into schist. If the heat is not too intense then it is changed to a rock called *slate* which splits into thin flat sheets that are used on roofs. Metamorphism also affects igneous rocks. For example, it can change granite into a striped rock called *gneiss* (pronounced nice).

Metamorphism and mountain building. Metamorphism may be caused by a nearby hot pluton, as in the case of the schist from Glendalough. More often, however, it is caused when rocks become very deeply buried and intensely heated. Very deep burial happens when powerful converging forces in the Earth's interior crumple and thicken the continental crust and raise mountain ranges like the Alps. (These converging forces are opposite to the 'pull-apart' forces that widen the Atlantic Ocean). A geological episode that builds mountains like this is called an *orogeny* (pronounced a-*rodge*-any).

Beneath the mountain range the rocks are buckled downwards into the mantle as a deep root, and it is here that high temperatures and squeezing cause metamorphism (Figure 15). The deep root is a bit like the underwater portion of an iceberg; just as an iceberg floats in the sea with its top showing above the water, so the thickened buoyant continental crust floats, as it were, in the mantle with its top sticking up as mountains. Later, when the mountains are being eroded away, the deep root (which is now made of metamorphic rock) bobs up and becomes exposed over a wide region at the Earth's surface.

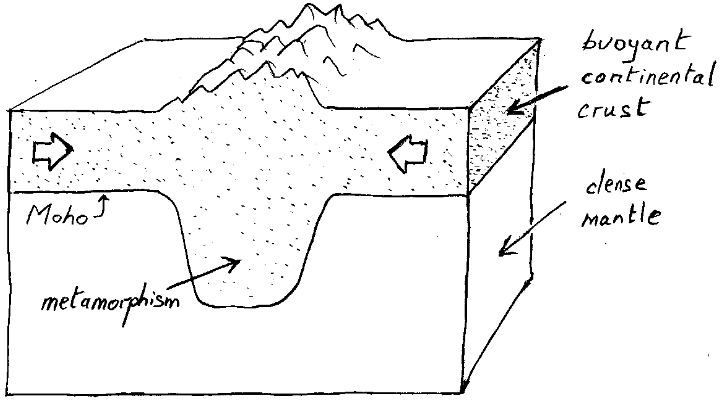


Figure 15 Block diagram showing the continental crust on top of the mantle. The continental crust is normally about 30 km thick. The block is cut through a mountain range whose root goes about 70 km down, deep into the mantle. The root is buoyant. It ‘floats’ in the mantle, holding the mountains up. The mountain range and its root were made when opposing sideways forces (shown by arrows) somehow crumpled the continental crust, making it a lot thicker. The crumpling process is called an *orogeny.* Rocks in the root become so hot and squeezed that they are changed to metamorphic rocks. In time, erosion will remove the mountains, the buoyant root will ‘bob up’, and the newly-formed metamorphic rock in the root will end up at the surface. The bottom of the continental crust is called the *Moho* (pronounced *moe*-hoe).

3.4 Partial melting and the rock cycle

During an orogeny, the high temperature in a mountain root may be go beyond metamorphism and cause *partial melting* of the rocks. When this happens, rock becomes a slushy mixture of solid grains and liquid. The liquid separates off and makes its way upwards as new magma which is usually granite magma. Partial melting thus links igneous rocks to metamorphic rocks. With this link established, we can now put *all* processes that affect sedimentary, igneous and metamorphic rocks onto a single conceptual diagram called the *rock cycle* (Figure 16).

Starting on the Earth’s surface, rocks undergo weathering and erosion (1) and the products get transported ‘downhill’ (2) into a basin where they accumulate as sediment (3). With burial and heating (4), lithification turns the sediment into sedimentary rock. With deeper burial and intense heating (5), metamorphism changes sedimentary rock into metamorphic rock. With even more heating, partial melting (6) leads to the formation of granite magma. The magma rises (7) and either intrudes the rock above (8) to form a plutonic igneous rock (granite), or rises straight to the surface and erupts (9) as a volcanic igneous rock (rhyolite). The rhyolite is weathered and eroded, starting the cycle over again. The granite is uplifted (10) and eroded, so it, too, eventually re-enters the rock cycle.

Two other circuits of the rock cycle result from uplift (10) of metamorphic and sedimentary rocks, respectively. Erosion leads to their exposure at the surface, and their weathered and eroded products (1) go back into the cycle as sediment.

Finally, two circuits are shown as dotted lines to avoid cluttering the diagram. In these, (a) volcanic, and (b) plutonic igneous rocks are buried, heated intensely, and changed (5) to metamorphic rocks directly, without first being eroded.

The rock cycle is confined to the continental crust. Basalt magma comes from the partial melting of peridotite in the mantle, so it is not part of the rock cycle. When basalt magma rises (dashed lines) into the continental crust (11) to fill a pluton, or to erupt as lava, it is entering the rock cycle for the first time.

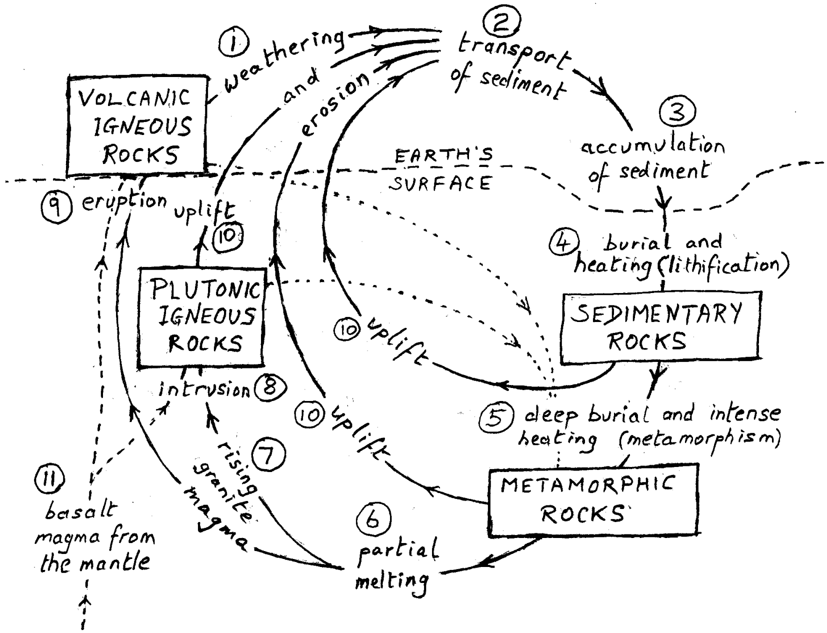


Figure 16 The rock cycle. The diagram is a simplified summary of the main processes affecting rocks, on the surface and at various depths below it within the continental crust. Rocks of all kinds at the surface are subjected to weathering and erosion (1). Eroded material is transported (2), and accumulates as sediment (3). It gets buried and heated (4) to become, firstly, sedimentary rock and then, if burial is deep (5) metamorphic rock. Intense heating causes partial melting (6) and granite magma is made. The magma rises (7) and either forms a plutonic granite intrusion (8), or escapes directly to the surface to erupt as a volcanic igneous rock (9). Uplift of the crust and erosion (10) bring sedimentary, metamorphic and plutonic igneous rocks back to the surface to begin the cycle again. Plutonic and volcanic igneous rocks can also be changed directly to metamorphic rocks by burial and heating (5). Basalt magma comes from the Earth's mantle (11) and joins the rock cycle for the first time when it enters the continental crust.

4 Geological time

Rocks are unimaginably old. You have read so far that in Ireland basalt erupted 60 million years ago during the Cainozoic Era, limestone began to form on the seabed 340 million years ago during the Carboniferous Period, and granite was intruded as magma 405 million years ago during the Devonian Period. But what are eras and periods? How many were there and what are their names? When were their starting times in millions of years? How are these times measured?

The complete span of geological time is divided up into long intervals known as *eras* which are subdivided into *periods*. Names of eras and periods are shown in Table 2. From oldest to youngest, nine geological periods to remember are (with the stressed syllable of each name shown in bold): **Cam**brian, Ordo**vic**ian, Si**lur**ian, De**von**ian, Carbo**nif**erous, **Per**mian, Tri**ass**ic, Jur**ass**ic and Cret**ace**ous. The order of these nine periods may be remembered from the first letter or two in each word of the mnemonic: *Camels often sit down carefully. Perhaps their joints creak.* These nine periods are grouped into three lots of three which, again, from oldest to youngest are known as the Lower Palaeo**zo**ic Era (pronounced pally-o-*zo*-ic) the Upper Palaeo**zo**ic Era, and the Meso**zo**ic Era (pronounced me-zo-*zo*-ic). The youngest era, called the Caino**zo**ic Era (pronounced cane-o-*zo*-ic) brings us up to the present day. It comprises the Tertiary and Qua**tern**ary periods. (A new alternative division of the Cainozoic is into what are called the **Pal**eogene and **Ne**ogene periods.) Time before the Cambrian Period is simply called the **Pre**cambrian. It is enormously long and is not strictly an era.

Era	Period	Start age in million years
Cainozoic	Quaternary*	2
	Tertiary*	65
Mesozoic	Cretaceous	145
	Jurassic	200
	Triassic	250
Upper Palaeozoic	Permian	300
	Carboniferous	360
	Devonian	415
Lower Palaeozoic	Silurian	445
	Ordovician	490
	Cambrian	543
Precambrian		4567

Table 2 The Geological Time Scale. The age of the *beginning* of each period of time is in most cases rounded to the nearest five million years. The names are traditionally listed ‘backwards’ because in nature the oldest layers of sedimentary rock are at the bottom of the pile. (*The Cainozoic has an alternative subdivision; see the text)

The ‘zoic’ ending means life – ancient life, middle life and recent life respectively for the Paleozoic, Mesozoic and Cainozoic eras. The Mesozoic is sometimes called the age of dinosaurs and the Cainozoic the age of mammals. At the end of each era very large numbers of organisms became extinct, and new, different organisms came to dominate during the subsequent era. The best known extinction event is perhaps the one at the end of the Mesozoic Era when a large asteroid struck the Earth causing catastrophic changes to the environment and the demise of the dinosaurs along with many other forms of life.

The geological periods were established in the nineteenth century from the presence of fossils – remnants of ancient organisms – in sedimentary rocks. Because life was evolving through time, rocks of a given period were found to contain fossils that are diagnostic of that period. The order of the geological periods was worked out using the simple principle that in a stack of horizontal sedimentary beds, the oldest are at the bottom and the youngest at the top.

It was not until the middle of the twentieth century that it became possible to measure the actual ages of rocks (in millions of years). The method used is based on natural radioactivity, and its application to the dating of granite will be explained in Section 6.5. It turns out that the beginning of the Cambrian Period was 543 million years ago, and the beginning of the Cainozoic Era (when the asteroid struck) was just 65 million years ago. Another interesting date is the age of the Earth, which we know (from studying meteorites) began to take shape as a planet 4567 million years ago. The oldest rock in Ireland (a rock similar to granite found on the island of Inishtrahull off the northern coast) is 1779 million years old. The start of the Quaternary Period is about 2 million years ago. It marks the beginning of a succession of many cold icy phases in the Earth’s climate.

Geological time is almost unbelievably long. To visualise its length, it might help to imagine the age of the Earth compressed to a single year, starting on New Year’s Day. The oldest rocks in Ireland would be made on August 11, life in the Carboniferous seas would flourish around December 4, an asteroid would strike late at night on December 26 killing off the dinosaurs, and Christ would be born at 14 seconds to midnight on December 31. A full human life of seventy years would last only half a second.

5 The geology of Ireland

5.1 The geological map of Ireland

The simplified geological map of Ireland on the back cover of this booklet shows the regional distribution of layered rocks (i.e. sedimentary and interleaved volcanic rocks) based on their *age*.

The map is divided into just four age categories labelled A to D. Precambrian layered rocks (A) occur in Donegal, Connemara and Mayo. Lower Palaeozoic (Cambrian, Ordovician and Silurian) layered rocks (B) are located in a large triangle between Longford and the east coast, also in Leinster, in the south part of Mayo, and as ‘islands’ in the southern half of the country. Upper Palaeozoic (Devonian, Carboniferous and Permian) layered rocks (C) cover most of Ireland. Mesozoic and Cainozoic rocks have been combined together (D). They are virtually confined to Northern Ireland and include the basalt of County Antrim.

At the foot of the map is a subsurface section (from X to Y) across Ireland. It is greatly simplified, but illustrates how the rocks in the age categories A, B and C can be visualized as layers, with the oldest layer, A, at the bottom, and the youngest one, C, at the top. The cross section shows how the ‘islands’ on the map (of B surrounded by C, in the southern half of the country) represent places where the layers are domed upwards so that B is exposed at the surface where the overlying C layer has been removed by erosion.

Also shown on the map are the main exposures of granite (granite batholiths), labelled G, in counties Donegal, Galway, Wicklow/Carlow, and Down. Because the granite magma was injected from below into the sedimentary rocks, the batholiths do not form part of the layered sequence. Instead, they cut across the layers. The Wicklow/Carlow batholith on the X-Y section cuts layer A and layer B. However it does not cut across layer C. Instead, layer C extends over top of the granite. This is because sediments of layer C accumulated directly on the granite *after* it had been uplifted, eroded and exposed at the surface, and had then subsided to become the Carboniferous seabed.

In 2006 the Geological Survey of Ireland (GSI), in conjunction with the Geological Survey of Northern Ireland published a revised Bedrock Map of Ireland at a scale of 1:500,000. The map shows layered (sedimentary and volcanic) rocks in many different colours, each colour corresponding to the detailed interval of time when each layer was laid down. The map, and also a reduced version of it for schools, can be browsed and downloaded *free* from the GSI website (www.gsi.ie). Printed paper copies of the map can be purchased for €10 from the GSI.

5.2 Ireland’s geological history

What kinds of layered rock were formed during each of the four age divisions, A to D, on the simplified map? How do these relate to the history of Ireland’s geological past? The following summary reviews the history of Ireland’s rocks. Three selected stages in this history are shown as simple maps (Figure 17).

In the northwest, Precambrian sedimentary rocks (A) include sandstone, mudstone and limestone. These were originally deposited on the seabed 600 to 700 million years ago, but most were since changed into metamorphic rocks (quartzite, schist, and marble) because of an orogeny (mountain building event) about 470 million years ago during the Ordovician Period. (The Precambrian sedimentary rocks, incidentally, have their own special name, *Dalradian*, pronounced dal-*raid*-ian; the orogeny also has its own name, which is *Grampian*).

Lower Palaeozoic rocks (B) are mainly sandstone and mudstone of Cambrian, Ordovician and Silurian age, plus Ordovician volcanic rocks. They accumulated on a deep ocean floor. For example the Ordovician mudstone that later became schist at Glendalough started out on this ocean floor, as did the sandstone of the Great Sugar Loaf Mountain which is Cambrian in age. The ocean in question has been named *Iapetus* (pronounced *yap*-it-us). The north-western half of Ireland lay on one shore and the south-eastern half was far away on the other shore (Figure 17A). The opposing shorelines gradually converged and by the end of the Silurian Period the Iapetus Ocean had gone and the two shorelines had met. The join runs diagonally across Ireland from near Clogher Head in County Louth to the Shannon estuary in the west (Figure 17B, dotted line).

A B C

Figure 17 Simplified snapshots of 'Ireland's' geography at three times in the distant past. A) 'Ireland' divided in two by the Iapetus Ocean during the Ordovician Period with volcanoes (red) on both shores. Blue is ocean; brown is land or shallow sea. B) 'Ireland' as dry land (pale brown) during the Devonian Period. The dashed line is where the two halves met after Iapetus disappeared. Rivers flow from the north with the sea to the south. Volcanoes are shown because granitic magma probably got to the surface when the plutons below were filling. C) 'Ireland' submerged under warm seas (blue) during the Carboniferous Period, about 340 million years ago.

Ordovician volcanoes erupted along both shores of the Iapetus Ocean. The line of volcanoes along the north-western shore somehow became caught up in the Ordovician orogeny (i.e. the Grampian orogeny) that changed the Precambrian sedimentary rocks (the Dalradian rocks) into metamorphic rocks. On the southeastern side of the Iapetus Ocean the volcanic rocks became interleaved with the Ordovician mudstones and sandstones. They can be seen today, for example, on the coast of County Waterford and at Portrane north of Dublin. The

Ordovician volcanoes had similarities to modern volcanoes in the so-called Ring of Fire around the Pacific Ocean. Their eruption coincided with a period when the opposing shorelines of Iapetus were getting closer.

When the two shorelines finally met at the end of the Silurian Period, another mountain building event (orogeny) occurred. (This orogeny has been named the *Late Caledonian orogeny*). It changed the mudstones to slate, and the Lower Palaeozoic rocks were raised up as mountains. A little later during the same orogeny, early in the Devonian Period, a little over 400 million years ago, granite magma rose from the hot, deep continental crust and formed clusters of plutons (batholiths) in the Lower Palaeozoic sedimentary rocks, causing local metamorphism (such as the formation of schist at Glendalough). Some granite magma possibly erupted above the plutons as rhyolite volcanoes.

The uplifted land became eroded, and granite was exposed at the surface by the time the land subsided again. Subsidence began in the south and, as the sea invaded, the coastline migrated northwards (Figure 17C). Upper Palaeozoic sedimentary rocks (C) accumulated on the subsiding surface. Mountains further to the north supplied sediment.

To begin with, late in the Devonian Period, before the sea flooded in, red sand and mud accumulated on an extensive, subsiding river flood-plain in what is now the south-west of Ireland. These became red sandstone and mudstone (called *Old Red Sandstone*). By the early part of the Carboniferous Period (about 340 million years ago) shallow seas covered the south, and shells accumulated on a tropical sea floor, eventually to become limestone. Later during the Carboniferous Period (about 310 million years ago) layers of sand, mud (and even plants) were accumulating on the still-subsiding seabed, later to become sandstone, mudstone and a little coal. By this time the limestone was buried far beneath.

During very late Carboniferous and early Permian times yet another orogeny affected Irish rocks. (This one goes by the name, *Variscan orogeny*, pronounced va-*risk*-an). It caused local folding of Carboniferous beds (e.g. see Figure 7) but little else, except in the south-west where Devonian mudstone was changed to poor quality slate. The rocks were raised up above sea level and eroded.

Mesozoic and Cainozoic age rocks are almost absent from the Republic of Ireland, perhaps because this part of the country was land, above sea level, and being eroded during much of this time. In Northern Ireland, however, there is red Triassic sandstone (called *New Red Sandstone*), and grey Jurassic shale as well as a distinctive layer of white limestone of Cretaceous age called *chalk*. A thick layer of basalt, of early Cainozoic (60 million years) age, rests on the chalk. It flooded onto the surface when the Atlantic Ocean started to stretch open.

For about the last 2 million years, the climate has switched many times between icy cold and mild. The last long icy spell (loosely known as the *Ice Age*) lasted for about 100,000 years, ending a little over 10,000 years ago. The melting ice left behind a blanket of glacial deposits, a few metres thick, of stony sand and clay.

Continental drift. One last point of interest is that Ireland's position on the planet has changed during its long geological history. Broadly speaking when the Iapetus Ocean vanished and the two halves of the country came together Ireland was in the southern hemisphere. It has slowly travelled northwards since. It passed through the tropics during the Carboniferous Period when corals grew in warm shallow seas, and humid forests flourished and later became coal. Before that, red Devonian sandstones and mudstones reflect its time in the southern hemisphere desert belt, while later the red Triassic sandstone in Northern Ireland ties in with its journey through the northern hemisphere desert belt.

The reconstruction of this journey has been worked out using a technique called *palaeomagnetism*. The Earth's magnetic field lines (those that make a compass point north) are horizontal at the equator, and increase in slope gradually with latitude to become vertical at the poles, where a compass would point at the ground. When sediment accumulates, or when basalt hardens, the newly formed rock captures a record of the slope of the magnetic field. This record can be measured in the rock today using a sensitive instrument called a *magnetometer*, so the latitude of the place where the rock was made can be worked out.

The island of Ireland did not exist, of course, until quite recently (geologically speaking). The area on the Earth's surface that is now Ireland has changed its geography many times. 'Ireland' was, in fact, for much of its history a tiny part of a giant continent called *Pangaea* (pronounced pan-*jeer*; from the Greek words *pan* = all, *gaia* = land; Figure 18). It was not so much 'Ireland' as Pangaea that drifted north. As it did so, it was first becoming assembled from older continents, then it was breaking apart, over 200 million years, into the present continents. The opening of the Atlantic Ocean was the latest phase in the break-up process.

Figure 18 Reconstructed map of the world as it was about 200 million years ago with a single giant C-shaped continent called *Pangaea* which was surrounded by ocean. Outlines of the modern continents are shown. Can you see Ireland? Also try to find India.

Pangaea is presented as a black and white outline map so that it can be photocopied and used in a class exercise, such as colouring and naming the continents, or cut up to make a jigsaw puzzle.

6 Further interesting things about rocks

6.1 Life in tropical Carboniferous seas

Evidence of ancient life may be found as fossils in sedimentary rocks of most ages. In Ireland, some of the most abundant and remarkable fossils are preserved in the Carboniferous limestone. Examples are illustrated in Figure 20. They include single and colonial corals, shell fish known as brachiopods, sedentary stalked creatures called crinoids (relatives of the modern sea lily), scuttling trilobites that resemble giant wood lice, delicate net-like fronds called bryozoa, and spiral shells from snails. As well as these large visible fossils, there are many tiny ones that can only be seen clearly with the help of a microscope. These are called microfossils. The study of fossils is known as *palaeontology*.

Fossils can be found almost everywhere that the Carboniferous limestone is exposed on the coast. Two of the most spectacular places to go are Hook Head in County Wexford and Stredagh Point in County Sligo (Figure 19). Near Dublin, the shore at Portmarnock is also worth looking at. If you get a chance to visit any of these places, think as you are walking on the gently sloping layers of limestone, that you are strolling over the ancient Carboniferous seabed. At Stredagh, in particular, you can see many large, stalk-shaped corals resting on their sides, just where they fell when they died. But in all these places take care not to venture close to the water's edge because freak waves have been known to wash people off their feet and into the sea.

Figure 19 A glimpse of the ancient Carboniferous seabed at Stredagh Point, County Sligo. This place is locally called Serpent Rock. The 'serpents' are actually fossils of large stalk-shaped corals that originally stood upright in their life position. Their formal fossil name is *Siphonophyllia gigantea*. The shaft of the geological hammer is about 35 cm long and gives an idea of the size of the fossils.

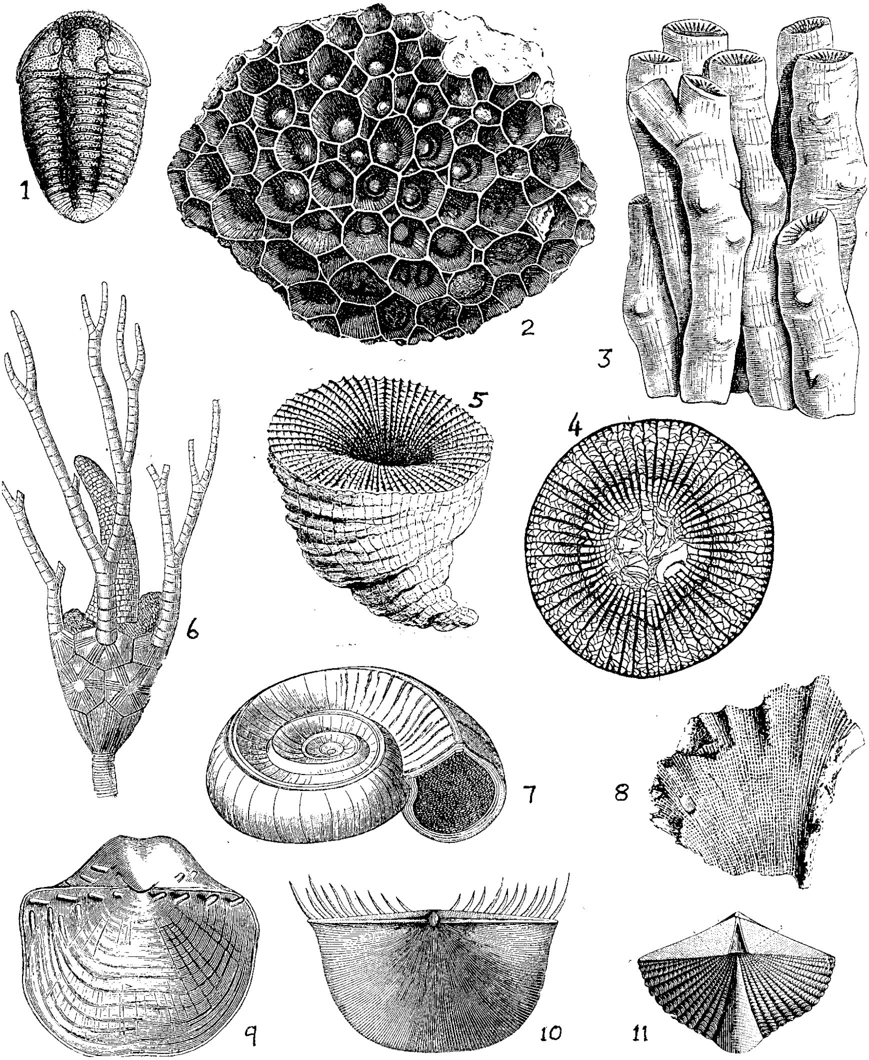


Figure 20 Selected drawings of the kinds of fossil that are preserved in the Carboniferous limestone. Names of the different types of organism are: a **trilobite** (1), **colonial corals** (2 and 3), **solitary corals** (4 and 5; note that 4 is a cross section of *Siphonophyllia* shown in Figure 20), a **crinoid** (6 – note that crinoids have long stems that break up soon after the organism dies. You are likely to find as fossils short lengths of their stems, or isolated segments that are usually about the size of thick shirt buttons), a **gastropod** (7), a **bryozoan** colony (8), and **brachiopods** (9, 10 and 11). Drawings are shown at roughly their natural size.

6.2 Making Ireland's mountains by erosion

Ireland's mountains are generally in the west and east of the country. In these regions the land surface was raised, probably during the Cainozoic Era, and erosion has since removed much of the uplifted rock. The mountains are what remain. Many of them are made of tough, resistant rocks like quartz sandstone and its metamorphic equivalent, quartzite, because the surrounding rocks are less durable and have been worn away more easily. Thick beds of quartz sandstone or quartzite form the Kerry Mountains, the Twelve Bens in Connemara, Croagh Patrick in County Mayo, Errigal Mountain in County Donegal and, as mentioned at the outset, the Great Sugar Loaf Mountain in County Wicklow. Near Dublin, on a more modest scale, the Hill of Howth and Bray Head are also made of quartz sandstone.

Granite contains a smaller proportion of quartz than sandstone, so it is not quite so durable. Erosion of granite leads to rounded mountains that contrast with the sharp sandstone peaks. Granite mountains are best developed in counties Wicklow, Donegal and Down (Mountains of Mourne).

Mudstone and limestone are quite easily eroded, so tend to form lowland regions. However, limestone hills do occur in parts of the west of Ireland, where perhaps the land surface was raised quite recently and erosion has not yet run its course. Ben Bulben in County Sligo and the Burren of County Clare are examples. Limestone slowly dissolves in rainwater, which is a very weak acid. In the Burren this process has led to so-called *karst* features with bare limestone 'pavements' (Figure 21). Sets of parallel vertical cracks (called *joints*) in the limestone have been widened out into fissures called *grykes* as rainwater over time has trickled down into them. The intervening blocks of remaining limestone are called *clints*.

Figure 21 View of a limestone pavement in the Burren. The parallel fissures in the limestone are called grykes.

The rainwater flows through the grykes down into a system of interconnected underground tunnels and caves that have also been enlarged by dissolution. In some open (air-filled) caves, however, the limestone is not dissolving up. Instead the water somehow acquires more dissolved calcium carbonate than it can manage. The excess calcium carbonate slowly adds on to the surfaces of vertical cylinder-shaped growths called stalactites and stalagmites. Stala***c***tites hang (on tight!) from the ***c***eiling, and stala***g***mites stand on the ***g***round.

6.3 Water, oil and gas in porous sandstone

When sand turns into sandstone, the grains will sometimes stick together only at points of contact, leaving open spaces or voids between them. Sandstone with voids is described as *porous*, and is economically very important because the voids may become filled with water, oil or gas.

Thick beds of porous sandstone are natural underground reservoirs (called *aquifers*) and are the main source of drinking water for people in many parts of the world. Water in an aquifer is called *groundwater*. It is pumped out through a well drilled into the aquifer, and it is replenished, or recharged, by rainwater that soaks down through the ground (Figure 22). Unless great care is taken, it is easy to spoil an aquifer by pumping it faster than it is being recharged naturally, or by letting contaminated water soak into it.

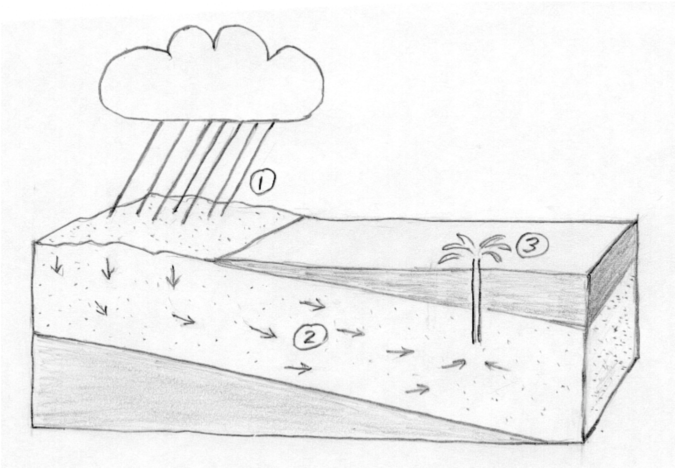


Figure 22 Block cut-away diagram showing a sandstone aquifer beneath the ground. Rainwater (1) soaks down into the sandstone and recharges the aquifer with *groundwater* (2) which completely fills the porosity. Groundwater is pumped out of a well (3). If the recharge area is higher than the well, and the layer above the aquifer is watertight, then the water will flow out of the well without the need of a pump. Wells that spontaneously flow in this way are described as *artesian* wells.

Porous sandstone is also the main kind of reservoir for oil and natural gas. Oil and gas have their origin in ancient plant and animal remains, particularly micro-organisms that get buried along with accumulating mud in sedimentary basins. As the mud gets warm and turns into mudstone, oil and gas are released from the organic remains. They usually leak out of the mudstone and travel upwards, eventually to escape at the surface. Sometimes the oil and gas find their way instead into the spaces (called pores) in porous sandstone, displacing the water that was there before. If the top of the sandstone layer happens to be sealed over by a dome-shaped watertight layer of mudstone, then the oil and gas remain trapped beneath the seal, with water below them (Figure 23).

Oil and gas are sometimes called *hydrocarbons* because they are made largely of the elements, hydrogen and carbon. Along with coal and peat they are known as *fossil fuels* because they come from the remains of ancient (fossil) organisms.

Oil companies spend a fortune looking for trapped oil and gas. They have been so successful in their searching that it seems that most of the oil and gas in the world has now been discovered. Despite this, the rate of consumption continues to rise worryingly, year on year, as the developed world becomes ever more dependent on oil and gas.

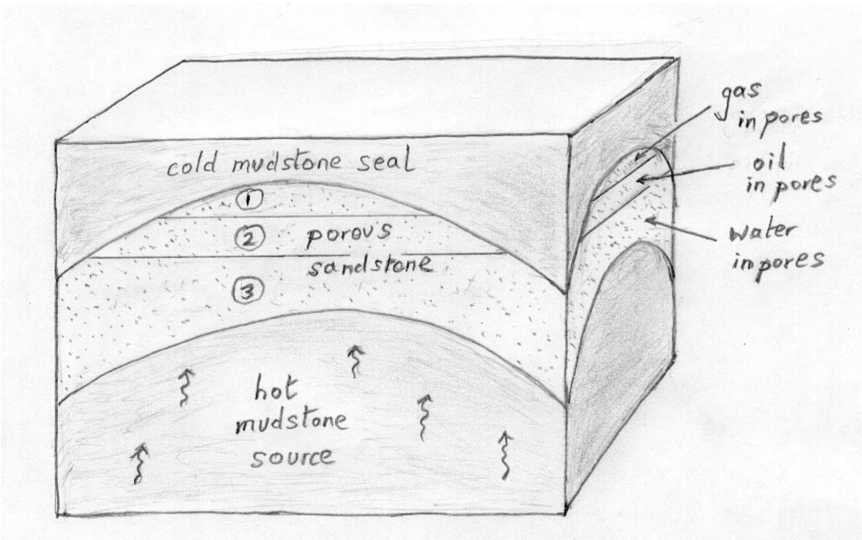


Figure 23 Block cross section through a hypothetical oilfield. Oil and gas are made when a source rock (usually mudstone with abundant organic remains) gets warm. The oil and gas migrate upwards. With luck they get trapped in a reservoir of porous sandstone in the shape of a dome sealed over by an upper layer of cool mudstone. Pores in the sandstone are filled, top to bottom, with (1) gas, (2) oil and (3) water.

6.4 Formation of zinc and lead ore in Ireland

Valuable ore deposits of zinc and lead are currently being mined in Ireland at Navan, County Meath, at Galmoy, County Kilkenny and at Lisheen in County Tipperary. The origin of this ore is linked to movement of groundwater in the distant past (Figure 24). During the Carboniferous Period the underground 'plumbing' was such that sea water (brine) soaked down several kilometres and became hot. It probably moved down fault planes and other cracks in the rock as well as through porous sandstone. Very small quantities of zinc and lead from the rocks became dissolved in the hot brine. The return flow, upwards, was along a major fault plane which led the brine through beds of newly-formed Carboniferous limestone. Here, as the brine cooled, tiny crystals of zinc sulphide and lead sulphide appeared. Over a long period a rich deposit of these zinc and lead sulphides built up within and beside the fault plane. Thus zinc and lead in low concentration were scavenged by hot brine from a large volume of rocks, and a high concentration of zinc and lead sulphides accumulated in one place, on and near the fault plane, producing an ore deposit.

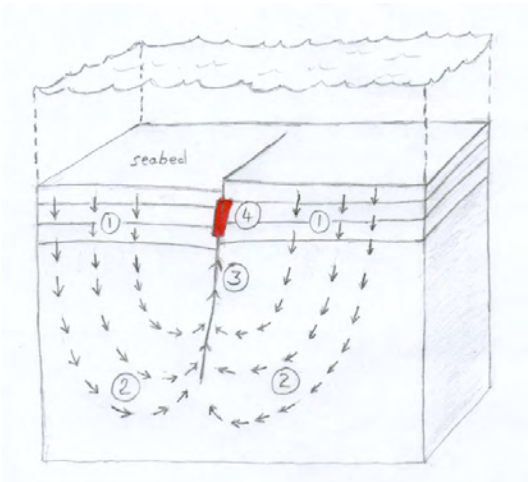


Figure 24 Simplified block cross section through part of Ireland during the Carboniferous Period when zinc (Zn) and lead (Pb) were accumulating in newly-formed layers of limestone below the seabed. Seawater (brine) seeped down (1), got hot, and scavenged scarce Zn and Pb over a large volume of rock (2). It then flowed up a major fault (3). Zn and Pb sulphide crystals formed where the fault intersected the limestone, concentrating a large quantity of ore which is shown in red (4).

6.5 How is the age of granite measured?

When granite magma cools and hardens, crystals of quartz, feldspar and mica grow within the liquid rock. Another mineral called *zircon* also grows, but it is rather scarce and too small to see without a microscope. Its grains are tiny transparent crystals, usually about one tenth of a millimetre long (Figure 25). Zircon provides a way of measuring the age of granite.

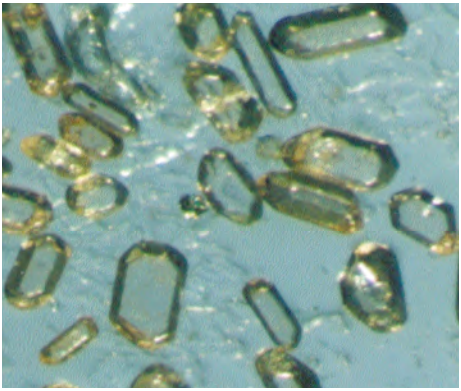


Figure 25 Tiny crystals of zircon seen through a microscope. They are up to about a tenth of a millimetre long. They were picked out of crushed granite from the Ox Mountains in County Sligo. The crushed granite is sieved, and then dropped into a very dense liquid called methyl iodide. Quartz, feldspar and mica float in this liquid, but zircon, being extremely dense, sinks and can be separated.

Zircon contains a tiny amount (usually less than 0.05%) of the rare heavy element, uranium. Uranium is *radioactive*. It is changing very, very slowly into a different element, lead. When granite magma cools, the newly formed zircon crystals do not contain any lead worth talking of. We can assume, therefore, that all the lead present today in an old zircon crystal was originally there as uranium.

Physicists using pure uranium compounds and an instrument like a Geiger counter have measured the precise speed at which uranium changes into lead. Geologists, using an instrument called a *mass spectrometer,* can measure the infinitesimal quantities of lead and uranium in a zircon crystal. Knowing the speed of change, and knowing the amounts of lead and uranium in a zircon crystal, it is possible to work out how long ago it was when the crystal had no lead at all. This is the age of the crystal, and hence the age of the granite.

The mathematical formula used in making the calculation is:

$$\text{Age of zircon (in million years)} = 14840 \times \log_{10}(1 + \text{lead/uranium ratio})$$

Figure 26 is a graph showing how the ratio of lead to uranium in a zircon crystal increases as the crystal gets older, back to 4567 million years ago (the age of the Earth).

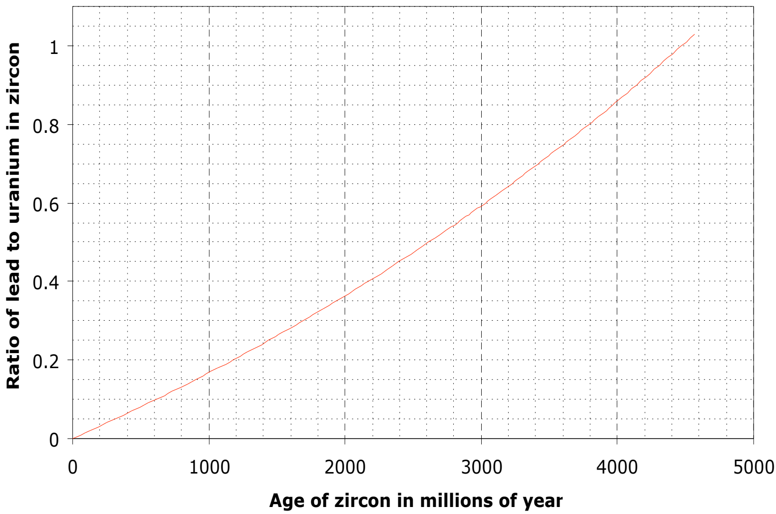


Figure 26 Graph for estimating the age of a zircon grain from its lead to uranium ratio.

(A small caveat is necessary here. Throughout the above discussion, 'uranium and lead' should strictly have been written 'uranium-238 and lead-206', respectively. The latter are specific kinds of uranium and lead, known as *isotopes*. It is these isotopes of uranium and lead that are measured by the mass spectrometer. As it happens, 99.3% of naturally occurring uranium is uranium-238 (the last little bit, 0.7%, is uranium-235), so if we were to measure the total uranium and total lead, instead of the amounts of the specific isotopes, the age would still be quite accurate. In fact, the first good age measurements of rock were determined this way nearly 100 years ago by a remarkable geologist called Arthur Holmes who measured lead and uranium in uranium ore. He showed in 1911 that a sample of uranium ore in a Devonian rock from Norway was 370 million years old. This age is remarkably close to what we now know to be the true age, and it was worked out long before isotopes were discovered, and even longer before mass spectrometers were invented.)

The use of radioactive elements for measuring the age of ancient objects is perhaps best known through *carbon-14* dating. Carbon-14 dating has a restricted application in geology, however, because it is limited to materials less than about 50,000 years old. It is widely used in dating archaeological remains.

Carbon-14 and uranium-238, incidentally, are just two out of many sources of natural radioactivity. Natural radioactivity is present everywhere in the environment, but it is normally at a very low level and harmless. However, the radioactive gas, *radon*, seeps out of the ground and very rarely it reaches dangerous levels when it leaks into poorly ventilated rooms.

6.6 How can liquid basalt come out of solid mantle?

Some people believe, wrongly, that the mantle is made of magma, which comes out of volcanoes as lava. Certain school textbooks blatantly reinforce this error. The Earth's mantle is solid. We know this to be true because a sensitive instrument, called a *seismometer,* can detect the slight jolt from a distant earthquake as seismic *S-waves* that have travelled through the mantle. S-waves are slow-moving sound waves. They have a sideways shaking motion that simply cannot pass through liquids. Their detection by a seismometer means that the mantle must be solid. So how, then, does liquid basalt come out of the mantle?

To understand the answer we need to know about two things: the 'melting point' of mantle rock (peridotite) and the temperature in the mantle. Experiments using a small furnace show that peridotite begins to melt at a temperature of about 1100°C. However, using a specially designed furnace in which peridotite is compressed as well as heated, it has been found that melting begins at a higher and higher temperature the more the peridotite is compressed. For example, when the compression is the equivalent of being buried to a depth of 200 km, melting starts only after the temperature gets to 1800°C (Figure 27). The second thing is that although the temperature below the ground increases 20°C with every kilometre of depth (see Figure 5), it cannot keep increasing like this forever. If it did, the temperature 100 km down would be about 2000°C and the

.

Temperature below the surface in °C

Depth below the surface in kilometres

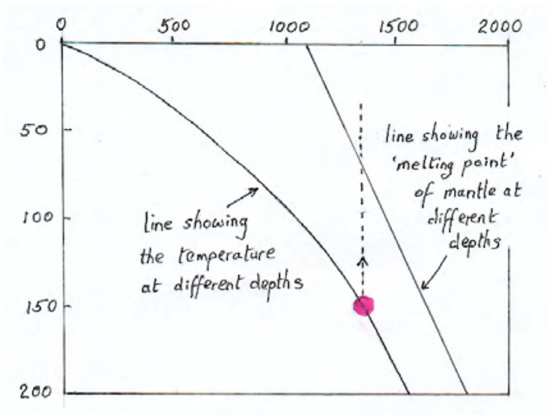


Figure 27 Graph showing an estimate of how temperature rises with depth down to 200 km below the surface. The purple spot shows the mantle is at nearly 1400°C at 150 km depth. The line on the right shows the 'melting point' of mantle rock. The 'melting point' increases from about 1100°C at the surface to about 1800°C 200 km down. If the hot mantle at 150 km depth moves upwards (arrow) at 2 cm per year it will stay hot and eventually cross over the 'melting point' line on the right. When it does so, it will partially melt and basalt magma will separate out from it.

mantle would be molten. Yet we know from the S-wave evidence that it is solid. The temperature very deep under the ground must therefore follow a curved line which stays below the 'melting point' of mantle, like that shown in Figure 27.

From this curved line, the temperature at 150 km depth is almost 1400°C, consistent with the mantle being solid, yet well above the temperature at which it would start to melt at the surface. If this hot mantle at 150 km down could somehow move upwards, then it would be easily hot enough to start melting.

This is exactly what happens in the mantle beneath Iceland. As the continents on each side of the Atlantic move apart, a gap across the middle of Iceland is continually opening by about 2 centimetres per year. Hot mantle material from a great depth continually moves upwards, also at the same slow rate, to fill the widening gap (Figure 28). The mantle peridotite is solid, but it can move very slowly because it is so hot. By the time the rising mantle gets to within 30 or 40 kilometres from the surface it will have partially melted, and about 25% of it will have separated off as liquid basalt, leaving 75% as solid, left-over peridotite. The liquid makes its way to the surface where it erupts as basalt lava.

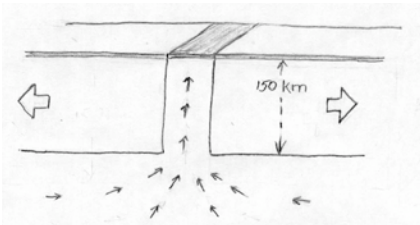


Figure 28 Simplified diagram of the origin of Iceland's volcanoes. 'Pull-apart' forces (arrows) open a gap into which very hot mantle rock 'flows' upwards. As the hot rock gets shallower it will eventually begin to melt and make basalt, as described in Figure 27. The basalt ends up forming a thin layer at the surface (shaded) with the remaining unmelted peridotite just below.

'Melting point' is written in quotation marks here because mantle peridotite does not strictly have a melting point, like ice for example, at which it becomes totally molten. 'Melting point' is the temperature where melting just *begins*. An extremely high temperature of 1850°C is needed for peridotite to melt completely. From 1100°C to 1850°C peridotite has a slurry-like consistency that starts of stiff and gets more and more liquid as the temperature increases.

Why does the 'melting point' get higher with depth? The reason is that peridotite, like most solids, expands when it melts. (Ice is a remarkable exception to this rule. When ice melts it shrinks.) Consider the mantle at 150 kilometres depth. The weight of the rock above it is truly enormous. The resulting pressure is about 25,000 times greater than the pressure of air in a car tyre. The rock is compressed so tightly that, despite being at 1400°C, it is prevented from expanding and so it cnnot start to melt.

7 The unifying mechanism: plate tectonics

Tectonics (from the Greek word, *tecton* = a builder or mason) is a term which means building geological structures, like mountain ranges and ocean basins. Plate tectonics is a theory of the Earth which links the formation of a wide array of geological structures to a single mechanism. Before it was formulated in the late 1960s, geologists knew about uplift and subsidence. They knew about the mantle and the Earth's continental crust, and that powerful sideways forces crumpled and doubled the thickness of the crust during episodes of orogeny (mountain building and metamorphism). They even knew that the Atlantic Ocean was opening and basalt was erupting along its central axis.

The breakthrough that brought all these disparate processes together was the realisation that the uppermost mantle (down to about 150 km depth) makes a very strong outer layer to the entire Earth because it is relatively cool. Below about 150 km the mantle is hot and weak and, although it is still solid, it behaves more like plasticine than rock. The strong outer layer, typically 150 km thick, is cracked into separate pieces, like crazy paving. It comprises a dozen or so separate 'paving slabs'. These slabs are not flat, of course, but curved so that they fit the Earth's spherical shape. They are called *plates*. Now plates move over the surface of the globe independently of each other, sliding on the hot, plasticine-like mantle below. What makes them move is not altogether clear, but possibly they are pulled along and jostled by slow 'turn over' in the hot plasticine-like mantle which is being heated by natural radioactive elements like uranium.

The Earth's continents are rather incidental to the plates. They are made of *continental crust*, about 30 kilometres thick, and are embedded in the upper surfaces of plates. As the plates move, the continents simply ride along passively on their backs like passengers. The continental crust, as mentioned before, is not as dense as the mantle, so it 'floats' on top and mostly sticks out as dry land (Figure 29, inset). In contrast, where there is no continental crust the plate is submerged beneath several kilometres of ocean water.

Most of the geological 'action' happens near the edges of plates where they move apart and where they converge. A hypothetical cross section through four plates and three boundaries (Figure 29) serves to illustrate some of this action. On a map of the world, the plates are easily picked out because their edges correspond to major earthquake zones (Figure 30).

Where plates are moving apart, hot mantle wells up very slowly from 150 km depth and fills the widening gap (Figure 29(1)). As it rises it partially melts to make basalt magma. This process was just explained in Section 6.6 on the formation of basalt under Iceland. When the mantle cools it simply becomes welded to the plates on either side of the gap, adding to their growing size. The topmost level of the newly added plate is made of basalt, and just below this is mantle that partially melted and lost its basalt. Together the basalt cap and underlying basalt-free mantle amount to a re-arranged version of the original mantle. Thus, all rock below the ocean floors can be thought of as being made entirely of mantle, albeit assembled in a new way. The topmost layer of basalt, incidentally, is a few kilometres thick and is called the *oceanic crust*.

Where plates converge, then one of them takes a dive, sliding back into the hot mantle, while the other rides over it. The outcome of convergence depends strongly on whether or not continental crust is embedded in the diving plate.

If there is no embedded continental crust in the diving plate, then it slides down easily, leaving a deep trench in the ocean floor where its descent starts (Figure 29(2)). Huge volcanoes erupt on the over-riding plate. The origin of these volcanoes is not properly understood. It seems that the hot plasticine-like mantle must rise and start melting, but there is no obvious widening gap to help it rise. Nevertheless, it does melt and basalt is produced.

The over-riding plate may, or may not, have embedded continental crust. If it does, as in Figure 29(2), basalt magma may gather as a huge intrusion deep in that continental crust, where its will heat the rocks and make granite magma by partial melting. The silica-rich granite magma can then mix with the silica-poor

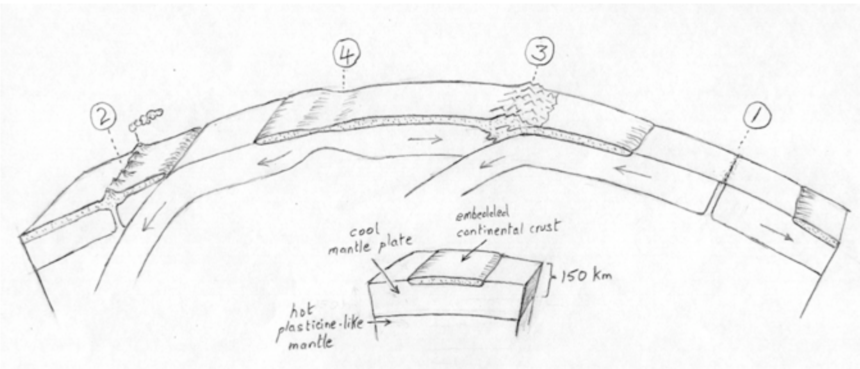


Figure 29 A hypothetical cross section (not to scale) through the outermost few hundred kilometres of the Earth. It shows parts of four plates, about 150 kilometres thick, with embedded continental crust about 30 kilometres thick. The plates rest on hot plasticine-like mantle (see labelled key). Three kinds of boundary are: (1) plates moving apart and growing beneath an ocean, with basalt lava erupting along the boundary, (2) plates converging, where the 'diving' plate has no embedded continental crust, and volcanoes are erupting above it, (3) plates converging where both plates have embedded continental crust which gets buckled and thickened and forms a mountain range with a deep root. Stretching and thinning of a plate (4) causes subsidence of the continental surface and formation of a sedimentary basin.

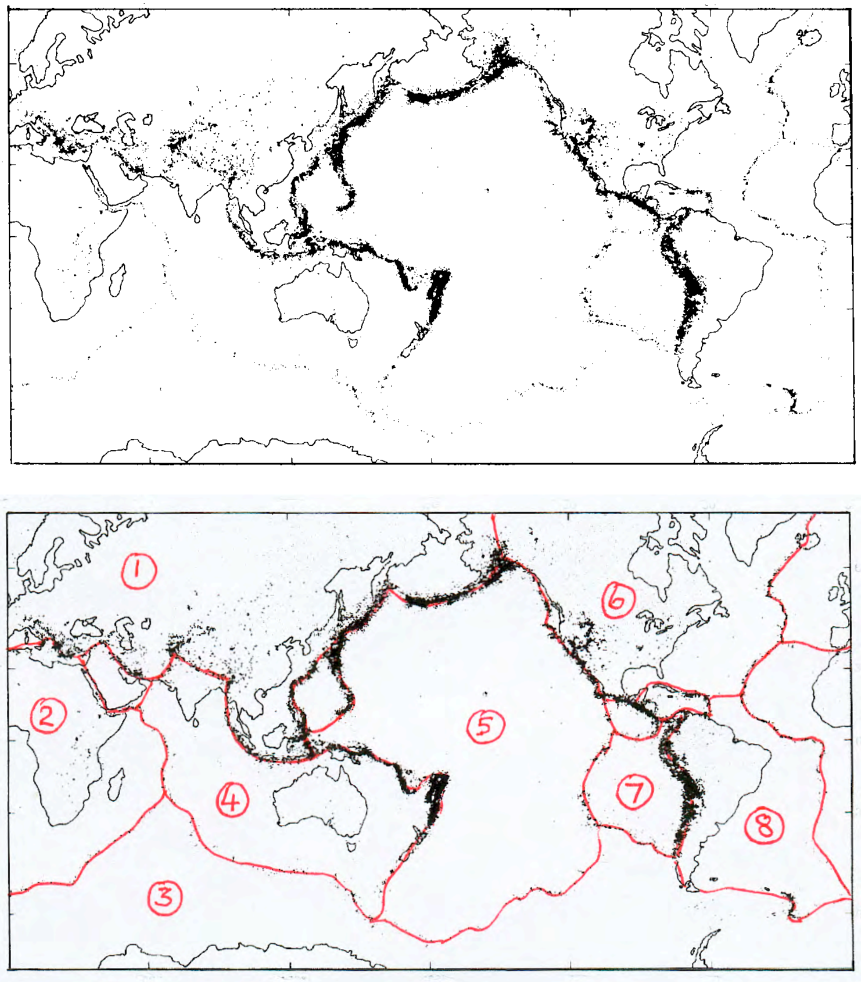


Figure 30 (*top*) Map of the world with the locations of recorded earthquakes shown as black dots. There are so many dots around the Pacific Ocean that they coalesce into fuzzy black zones.

(*bottom*) The same map with the dots joined up with a red line to show the edges of the plates. Eight major plates are numbered (1) Eurasian, (2) African, (3) Antarctic, (4) Australian/Indian, (5) Pacific, (6) North American, (7) Nazca, and (8) South American. Four minor plates shown (not numbered) are the Arabian, Philippines, Cocos, and Caribbean plates. Earthquakes are especially numerous where plates converge (e.g. beneath the Andes of South America), and are rarer where plates move apart (e.g. Iceland and the mid-Atlantic).

basalt magma to form intermediate magma. All three kinds of magma can then erupt at the surface, giving basalt, rhyolite and andesite volcanoes, respectively. The many volcanoes in the so-called ring of Fire around the Pacific Ocean, such as the Andes Mountains in South America, owe their origin to diving plates. (When the ancient Iapetus Ocean was shrinking during the Ordovician Period, many volcanoes were formed above diving plates in a similar way.)

If the diving plate contains embedded continental crust, then things get messy because the continental crust is buoyant and does not like to go down into the dense hot mantle (Figure 29(3)). In its effort to stay 'afloat' the crust peels away from the mantle layer of the diving plate and gets buckled and bent and generally much thicker. Mountain ranges are produced, with metamorphism and melting in their roots. This situation is an *orogeny*.

Buckling and thickening is particularly impressive where the diving plate and the overriding plate *both* have embedded continental crust. This is happening in an orogeny beneath the Himalayas today, where the Indian plate is trying to drag its continental crust beneath the Asian plate which also has continental crust.

The ancient orogeny in Ireland at the end of the Silurian Period (the so-called Late Caledonian orogeny) happened when the width of the Iapetus Ocean shrank to zero (i.e. when the last bit of ocean floor plate had taken its dive), and the opposing continental shorelines met each other and crumpled up.

Subsidence and uplift. Subsidence and the formation of sedimentary basins can also be linked to plate movement. Sometimes a plate with embedded continental crust can get stretched without actually breaking into two plates and starting a new ocean. In this case, the stretched plate simply gets thinner throughout (Figure 29 (4)). When the buoyant continental crust gets thinner, it doesn't 'float' so high in the mantle, and its surface sinks down below sea level. (This is probably what happened in Ireland during the Carboniferous Period when the land subsided and the sea invaded from the south.)

Uplift is more tricky. Orogeny obviously causes enormous uplift and erosion, bringing metamorphic rock to the surface. However, the cause of uplift of horizontal layers of sedimentary rock (e.g. those shown in Figure 6) is not really known. It seems that perhaps the mantle becomes locally overheated and expands, heaving the continental crust upwards as it does so.

To conclude this section on plate tectonics, three widely used terms need a brief introduction. An alternative word for 'plate' is *lithosphere,* which means 'stony [layer in the Earth's] sphere'). This, remember, is the outermost layer of cool, strong mantle about 150 km thick, with or without embedded continental crust. The warm, weak, plasticine-like mantle beneath it is known as the *asthenosphere*, meaning 'sphere without strength'. Finally, the technical term, *subduction*, describes the diving down of one plate under another when two plates converge.

8 Ideas for class work

Describe the six kinds of rock: This exercise in an excellent preparation for learning about the origins of the rocks. Pass the specimens around and ask students to write down the obvious things they can see – the colour, the kind of shape (flat or chunky), whether individual ‘bits’ (grains) are visible, and their nature. Can the rock be scratched with steel and does the scratched up powder fizz slightly under a drop of vinegar? These last two tests might be better done at the front of the class by one student for the others to see. If you can get hold of some dilute hydrochloric acid, instead of vinegar, so much the better.

Use the diagrams: Diagrams reinforce concepts. The diagrams in this book aim to be simple in design, and they are deliberately hand-drawn, often in black and white, so that they can be used in class. Where possible get students to copy them from the board, and colour and label them. With block diagrams it may make life easier to just draw the ‘front face’.

Rock cycle: On a large (e.g. A3) sheet of paper draw the flow lines of the rock cycle with four blank rectangles joined by the names of processes, and ask students to place the rock specimens on the right rectangle. Alternatively, have no text and ask students to place cards naming the processes as well as placing the rocks correctly. They can then copy the rock-cycle diagram into their books.

Geological time. To demonstrate the enormity of geological time, and the very brief duration of human existence on the planet, let a toilet roll correspond to the age of the Earth. Let four sheets equal 100 million years. Write 4600 million years (the age of the Earth) with a fat marker at the edge of the very first sheet and unroll (you will need a volunteer to hold the end and walk!). Check off every 100 million years and have a short list of events to mark on (e.g. age of the oldest rock in Ireland; starts of geological periods, age of Carboniferous limestone; age of the Giant’s Causeway basalt; the birth of Christ.) It works out roughly that a half centimetre is 1 million years, so half a millimetre line across the end of the very last sheet is the length of the last phase of the Ice Age (about 100,000 years), and the time since Christ lived is razor thin – one hundredth of a mm!

Geological maps: Photocopy the geological map on the back cover. Two maps will fit on an A4 sheet to save paper. Students simply colour the map, section and key. If you have access to the internet, you can browse or download free detailed geological maps from the Geological Survey of Ireland web site (www.gsi.ie). Find out as much as you can about the geology of your local area.

Plate tectonics: Make multiple enlarged copies of the earthquake map (Figure 30, top). Get students to draw the plate boundaries by ‘joining the dots’ (the answer is in the lower map) and name the plates. They can colour the continents brown and estimate the percentage of continental crust on each plate. They can also identify examples of the three types of boundary, 1, 2 or 3, that were considered in Figure 29, and, if possible, draw an arrow on each plate showing the rough direction it is moving in (hint: the Atlantic is getting wider, the Pacific narrower, and India is moving north to make the Himalayas). Younger students can simply name and colour the plates, or assemble a simple jigsaw made by copying the lower map onto card and cutting it up. Students can estimate the annual increase of the Atlantic Ocean. Sixty million years ago, the original distance from Ireland to Greenland (see Figure 11) was about 800 km. It is now about 2000 km. So in 60 million years it has increased by 1200 km. Since 100 cm is a metre, and 1000 metres is a km, the total widening of the Atlantic has been 1200 x 100 x 1000 cm. This comes to 120 million cm in 60 million years, or 2 centimetres in one year.

Graph reading: Make sure students are happy with reading graphs. For example, you can use the graph in Figure 5 to find out how hot it is 2.5 km below your school, and how deep you need to drill to reach a temperature of 80°C. Also use the graph in Figure 26 to estimate the ratio of lead to uranium in zircon from a meteorite that was formed 4567 million years ago, and to estimate the age of a zircon grain whose lead to uranium ratio is 1 to 10 (i.e. 0.1).

Fossils: Photocopy the page of drawings of fossils from the Carboniferous limestone, but without names. Supply cards with written descriptions and names. Ask students to write the correct name beside each fossil. Younger students might like simply to write the names and colour the drawings.

If you know of other practical ways of reinforcing the ideas in this book, please send them to isanders@tcd.ie. Suggestions will be displayed on the Trinity College Geology web page, www.tcd.ie/geology/outreach

9 Further information and reading

Web sites. Type any of the italicized terms in this booklet into *Google* for a choice of reading to reinforce and develop your understanding. Also check the websites of the Geological Survey of Ireland (www.gsi.ie) and the Geological Survey of Northern Ireland (www.bgs.ac.uk/gsni) for maps and publications, including the books *Understanding Earth Processes, Rocks and the Geological History of Ireland* (GSI) and *The Geology of Northern Ireland* (GSNI).

General books: Richard Fortey's *The Earth: an Intimate Biography* is a charmingly anecdotal account of the rise of modern geology written by a top-ranking scientist with the pen of a poet.

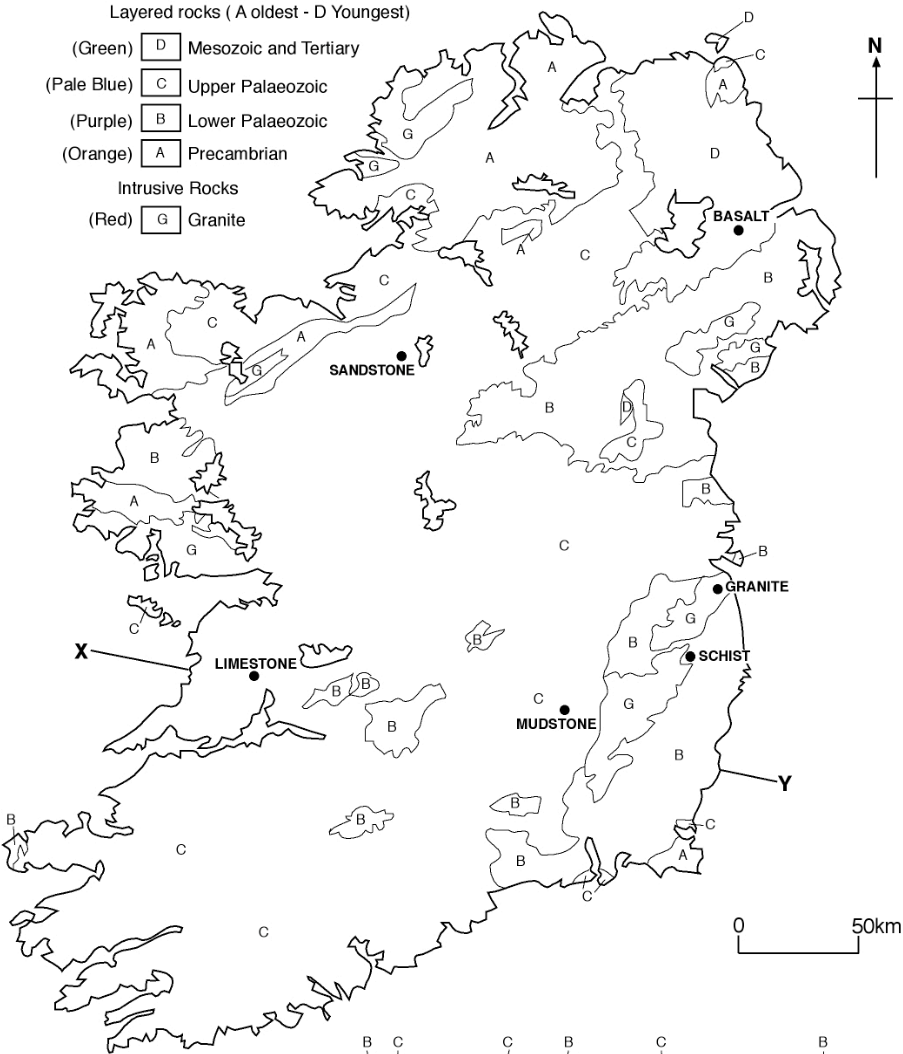
Bill Bryson's *A Short History of Nearly Everything* is an engagingly written layperson's explanation of science, much of it relating to geology.

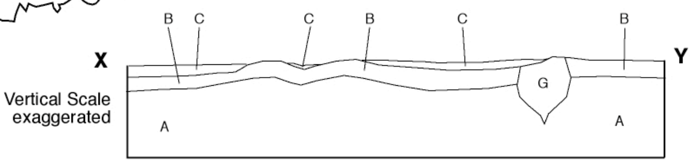
Magazine: *Earth Science Ireland*. This twice-yearly publication is funded by various sponsors and goes free to schools in Ireland. To register for your personal copy contact the editor, rbazley@btinternet.com

10 Index of technical terms

Andesite 21, 44
Anticline 15
Aquifer 35
Artesian well 35
Asthenosphere 44
Basalt 16
Batholith 20
Bed 14
Bedrock 5
Breccia 15
Calcium carbonate 13, 35
Cainozoic Era 26
Carbon-14 39
Chalk 30
Chlorite 14
Clint 32
Coal 13
Conglomerate 14
Continental crust 21, 42
Continental drift 31
Crystallise 19
Dalradian 29
Density 21, 22
Dip 15
Dyke 20
Exposure 5
Extrusive rock 19
Fault 15, 16
Feldspar 10, 19
Fold 15
Fossil fuel 35
Gabbro 20
Geological timescale 26
Glacial deposits 6
Gneiss 23
Grampian orogeny 29
Granite 18
Groundwater 35
Gryke 32
Hard water 13
Hematite 14
Hydrocarbons 35
Iapetus 29
Ice Age 6, 30
Igneous rock 19
Intrusion 18
Intrusive rock 20
Isotope 39
Joint 15, 32
Karst 32
Lava 17
Late Caledonian orogeny 30
Lime 9
Limestone 13
Lithification 11
Lithosphere 44
Magma 17
Mantle 17
Marble 23
Mass spectrometer 38
Mesozoic Era 26
Metamorphic rock 23
Mica 10, 19
Mineral 10, 19
Moho 22
New Red Sandstone 30
Oceanic crust 43
Old Red Sandstone 30
Orogeny 23
Palaeomagnetism 31
Palaeontology 32
Palaeozoic Era 26
Pangaea 31
Partial melting 24, 41
Peridotite 21
Plate tectonics 42
Pluton 18
Plutonic rock 19
Porous rock 35
Pyroclastic rock 20
Quartz 10, 19
Quartzite 23
Radioactivity 38
Radon 39
Rhyolite 20
Rock cycle 24
Rock salt 14
Sandstone 11
Schist 22
Sediment 13
Sedimentary basin 13
Sedimentary rock 13
Seismology 22
Seismometer 40
Shale 12
Silica 21
Silicates 21
Sill 20
Slate 23
Strata 14
S-waves 40
Subduction 44
Syncline 15
Variscan orogeny 30
Volcanic ash 20
Volcanic rock 19
Zircon 38

GEOLOGICAL MAP OF IRELAND





Subsurface cross section X - Y