Understanding Earth Processes, Rocks and the Geological History of Ireland

A companion to the 1:1,000,000 scale Bedrock Geological Map of Ireland

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Geological Survey of Ireland

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A COMPANION TO THE 1:1,000,000 SCALE BEDROCK GEOLOGICAL MAP OF IRELAND

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PREFACE

Geography is a descriptive science that relates the distribution and interaction of the physical, biological and cultural aspects of the World in which we live, past and present.

Almost everything we take for granted in our daily lives is either grown in the soil, derives its nutrients from plants that grow in the soil, or is taken from the sub-surface. The soil in turn is derived from organic matter and the breakdown of rock materials so everything is really dependant on geology.

This book attempts to describe and explain the geography and geology of the physical features of Ireland, as depicted on the accompanying geological map of Ireland. The geological map is simply a representation of the sub-surface of Ireland if all the soil and glacial deposits were removed down to the solid bedrock. As such, it is an interpretation, as in most places rock is not exposed at the surface. While the map depicts the geography (i.e. distribution) of rocks of different ages and types at the present, the book gives a historical geography (palaeogeography) of each Earth period, as shown in the map legend. Within each Earth period (or sub-period), physical processes and the resultant environments are described and explained and related to examples in different parts of the world today. For example, rivers in an arid semi-desert environment deposited the sediment (which later was turned into rock) in the Devonian Period, when Ireland was positioned in the tropics, a position and environment analogous to much of present day Australia.

The new syllabus for the Geography Leaving Certificate in Ireland gives greater emphasis to geology and the geological processes that have shaped the landscape. It is hoped that this book will give an increased awareness of the importance of geological processes, rocks and minerals, to everyday life. As such it relates to Core Unit 1 of the new syllabus ‘Patterns and Processes in the Physical Environment’. The book should also prove to be a useful resource in relation to students taking GCSE Geology at ‘A/ AS’ levels in Northern Ireland.

The book is written primarily as a resource for teachers, but will also be of interest to those enquiring students who want to know a little more than the bare minimum required to pass examinations, or indeed members of the general public who would like to know more about rocks and the origins of the landscapes of Ireland. We hope that it will inspire readers to take geology seriously in a geographical context and perhaps embrace it for its own sake. To this end we have included a short bibliography of other books, maps, pamphlets and websites that we hope will be useful to the enthusiastic teacher, student, or layperson in both a general and a more specific local context. We have attempted to keep technical terms to the minimum but where necessary they are explained in the text.

1 INTRODUCTION

The Earth is a dynamic planet. We are very aware of this in relation to the weather, which is perhaps the most popular topic of conversation in Ireland, enjoying, or suffering, according to your point of view, a maritime climate; but the dynamic Earth might not be so obvious in relation to the ground on which we walk and the rocks beneath. For example, Ireland is a part of the world least affected by earthquakes and has no volcanoes at the present. This, however, was not always the case in the past. Processes above and below the Earth's surface, atmosphere, oceans, continents, lithosphere, crust, mantle and core, not to mention the moon and the sun are interacting across the globe to continually modify, if only slowly to our eyes, the geography of the Earth's surface.

In this section, a basic understanding of geological principles, the tectonic cycle, the rock cycle, descriptions of common rock types, fossils, and the importance of geology and geological materials in everyday life will be given. The book then describes the geological history of each rock unit shown on the map in order, from the oldest to the youngest. A theme, or themes, for each unit are developed as appropriate with 'Study Boxes'. For example, the themes of plate tectonic subduction and the formation of volcanic island arcs, like the islands in the Sea of Japan today, are developed in the context of the Ordovician Period. The Carboniferous Limestone chapter, on the other hand, explores the process of limestone formation, karst development, and the importance of mines and quarries. Lastly, although it does not appear on the map, the Quaternary (Pleistocene) Ice Age and post-glacial Holocene processes and deposits are described, because of their importance in Irish geology and geography and their significance to the economy.

1.1 BASIC GEOLOGICAL PRINCIPLES

Geological processes are not random, but follow a well-worn pattern that is repeated in cycles, such as the tectonic cycle and the rock cycle (described below). Since the Earth was formed about 4,500 million years ago, nothing has been added to it apart from minor incursions of meteorite material and yet the world is very different now because of the effects of these cycles. Ultimately, the engine of change in the cycles is the heat derived from the Earth's interior, driven by the decay of natural radioactive mineral isotopes.

One of the earliest principles established in geology and still used in the construction of geological maps and in geological interpretation, is the '**principle of superposition of strata**'; this was proposed by the Danish geologist and anatomist Nicholas Steno (1638 - 1686). The principle simply means that in a sequence of sedimentary rocks, the oldest rock deposited is at the bottom of the pile and rocks lying on top of it become successively younger higher up and that sedimentary rock layers were originally deposited flat-lying (see Fig. 1.1). This is more difficult to interpret in areas where the rocks have been folded and overturned, but can be used in most cases to establish the relative age of rocks. It can also be used when an igneous rock intrudes into and cuts across already existing rocks to establish a sequence of events.

Figure 1.1 *Flat lying beds of Carboniferous (Namurian) sandstone and mudstone, the youngest beds at the top, West Clare.*

ERA	AGE (million years)	PERIOD	MAIN ROCK TYPES	ENVIRONMENTS	TECTONIC EVENTS
CENOZOIC	1.8	Quaternary*		**Ice Age:** Ireland covered and shaped by ice.	
	65	Tertiary	Clay Granite & gabbro intrusions Basalt	**Lake & swamp:** Mid-Tertiary clays and lignite deposited in large lake (the precursor to L. Neagh). **Volcanoes:** Vast amounts of basalt lava flood NE Ireland during Early Tertiary.	**North Atlantic rifting:** Greenland separates from Europe as Atlantic rift extends northwards.
MEZOZOIC	144	Cretaceous	Chalk	**Shallow 'Chalk sea':** Ireland is land area for much of time. Pure limestone deposited in late Cretaceous shallow sea, probably over whole of Ireland.	
	203	Jurassic	Shale & limestone	**Sea basins:** Mud and limestone deposited in early Jurassic shallow sea in NE, while rest of Ireland is land. Thick accumulations of sediment as today's offshore basins form.	**Early Atlantic rifting:** American & European Plates begin to separate, forming Atlantic ocean between.
	250	Triassic	Sandstone 'New Red Sandstone'	**Desert:** Red sandstone formed in arid desert dunes and playa lakes. Evaporite (salt & gypsum) in hypersaline lakes.	**Extension:** Marine basins around Ireland formed by stretching of the continental crust.
PALAEOZOIC	298	Permian			**Variscan Orogeny:** Minor effects in Ireland of mountain building in Central Europe.
	354	Carboniferous	Sandstone & shale Limestone Sandstone & shale	**River deltas & swamps:** Sand and mud deposited in large river delta systems advancing into sea. Coal formed in hot swamps. **Tropical sea:** Limestones deposited in warm tropical sea. **Advancing sea:** Sand and mud deposited in shallow sea advancing from south to north over eroded Devonian mountains.	
	410	Devonian	Sandstone 'Old Red Sandstone' Granite intrusions	**Mountains & rivers:** Red sand and mud deposited among semi-arid mountains by large river systems. Subsiding basin in SW receives vast thickness of sediment.	**Acadian Orogeny:** Mountain building as Iapetus finally closes, joining NW and SE halves of Ireland.
	440	Silurian	Sandstone & shale	**Ocean basin:** Sand and mud deposited in narrow ocean basin and continental margins as Iapetus closes.	
	495	Ordovician	Sandstone & shale Shale & sandstone, basalt & rhyolite Gabbro - granite intrusions	**Ocean depths & Ring of Fire:** Sand and mud deposited in deep ocean by turbidity currents. Ring of volcanoes around ocean formed above subduction zones	**Grampian Orogeny:** Mountain building and metamorphism in NW as volcanic arc collides with continental margin when Iapetus begins to close.
	545	Cambrian	Sandstone & slate Quartzite in above	**Shelf sea:** Sedimentary rocks deposited on continental shelf in SE.	**Iapetus ocean opens:** Ancient continents rift apart to form Iapetus ocean crust between.
PRECAMBRIAN*	1800 4500		Schist & gneiss Quartzite in above	**Ancient continents:** Ireland's oldest rocks formed 1800-1900 million years ago as igneous intrusions; metamorphosed to gneiss by Grenville mountain building. Sedimentary rocks (Dalradian), including deposits of global ice age, formed at rifting continental margin in NW.	**Cadomian Orogeny:** Metamorphism of oldest rocks in the SE. **Grenvillian Orogeny:** Mountain building and metamorphism of oldest rocks in the NW.

* Precambrian and Quaternary not to scale

Volcanic rocks, Precambrian to Carboniferous

Gap in geological record (no rocks preserved)

Figure 1.2 *The geological timescale*

Subsequently the 'father' of modern geology, James Hutton (1726 - 1797), of Edinburgh, established the principle of **uniformitarianism,** that is, '**the present is the key to the past**'. This means that processes, structures, and landforms we can observe and describe today in the rocks and sediments, can be used to interpret the past. Ripples observed on an ancient rock surface can be compared, for example, with ripples found today in a river, on a beach, or in shallow seawater. Further information contained in the rocks may be used to narrow down the options as to whether the rock was originally deposited in the sea or in a river. For example, the rock might contain fossils of animals similar to animals found only in the marine environment at the present time. Similarly, rocks, like the basalt at the Giant's Causeway, can be compared with volcanic rocks forming today and conclusions drawn as to the mode of formation of the Giant's Causeway. The principle does not always work, but is a good general rule to follow. Sometimes a bit of lateral thinking is necessary. For example, there are fossil groups, which have no living relatives, such as the ammonites in Mesozoic times, but much can be deduced about their mode of life by comparison with distantly related animals like the present day nautilus. When interpreting an ancient environment it is important to take all factors into account before reaching a conclusion. Carrying out a comprehensive description is the key to interpretation.

An 18th century group of geologists, the **Neptunists,** led by Abraham Werner (1750 - 1817) of Freiberg in Germany, believed in '**catastrophism**'. They thought that most geological change was caused by rare catastrophic events like Noah's flood or periodic violent volcanic eruptions. At that time, people generally still believed that the Earth was only 6000 years old, a figure that had been calculated from the genealogies contained in the Bible by James Ussher (1581 - 1656), Vice-Chancellor of Trinity College Dublin and Archbishop of Armagh. The notion of an 'old Earth' took time to develop. Hutton believed that the Earth was old, but he had no way of establishing an absolute age for the Earth. He proposed that geological change was gradual; that sedimentation proceeded slowly day-by-day, year by year, and so on. Hutton also noticed repeated cycles of uplift and erosion in the rock record. Charles Lyell (1797 - 1875), a student of Hutton, noted that fossils could be used to determine the relative age of different rock strata and introduced the idea of stratigraphy, to separate different ages of rocks (Fig. 1.2). The Irishman John Joly (1857 - 1933), Professor of Geology and Mineralogy at Trinity College Dublin established an old age for the Earth of 80 - 90 million years by calculating how long it had taken for salts to accumulate in the oceans from erosion of the land by rivers. The age was a gross underestimate because the method (suggested by Edmund Halley, 1656-1742, of Halley's Comet fame) did not take into account various ways salts are removed from the oceans. In 1913, however, together with Sir. Ernest Rutherford at Cambridge, he established a 400 million year old age for the beginning of the Devonian Period, based on the decay of radioactive minerals (see Study Box 2.2), a calculation that is in line with modern dating and was a large step towards determining the currently accepted age of the Earth.

Today most geologists would accept that the debate between gradual change and rapid or catastrophic change lies somewhere between the two extremes. Americans Stephen J. Gould and Niles Eldredge put forward a theory in 1972 called '**punctuated equilibrium**'. This was applied to evolution, but is equally applicable in geological interpretation. Gould and Eldredge showed evidence that major changes or evolutionary developments in animals occurred in spurts. In between these sudden spurts only small changes took place (stasis). A good example is the major extinction of fossil groups at the end of the Cretaceous Period (see section 13.2) after which new forms arose and took their place. There are analogous situations in other areas of geology, such as sedimentation, when occasional storms, hurricanes, volcanic eruptions, and other phenomena suddenly effect considerable change, after which there is a quiet period until the next sudden event.

1.2 THE TECTONIC CYCLE

1.2.1 THE INTERNAL STRUCTURE OF THE EARTH

The internal structure of the Earth (Fig. 1.3) is divided on the basis of compositional layering into the crust, mantle, and core.

The crust, which is the outermost layer of the Earth, is rigid, and very thin compared to the mantle and core. It is divided into continental crust, which averages 30 - 40 km thickness, and oceanic crust, which is about 5 - 7 km thick. Continental crust can be much thicker in the roots of mountain chains like the Andes, where it varies from 40 km at the Pacific coast to 70 km in depth beneath the Altiplano and Western Cordillera in Peru.

The boundary between the base of the crust and the mantle is called the Mohorovicic Discontinuity, or Moho for short (Fig. 1.3). It is named after the Croatian scientist Andrija Mohorovicic. It marks a sudden rise in rock density, as the mantle contains more iron, magnesium and calcium than the crust, and can be identified seismologically (see below). The mantle is about 2,900 km thick and is made up mostly of hot ductile rock.

The core of the Earth is about 3,500 km thick (in radius) with the centre of the Earth at 6,370 km from the surface. It is divided into an outer liquid core and a 1,270 km thick solid inner core. The electrically conductive liquid iron in the outer core seethes like boiling water in a pan on a hot stove and has whirlpools powered by the Coriolis forces of the Earth's rotation; these motions generate the Earth's magnetic field.

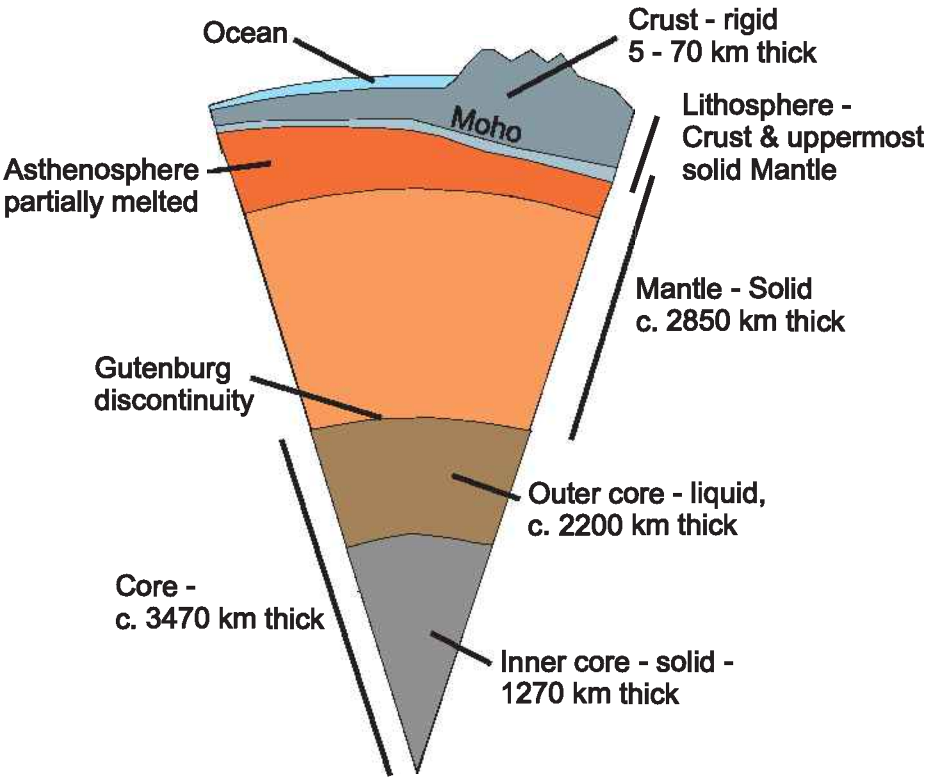

Figure 1.3 *The Internal Structure of the Earth*

The Earth's internal structure can also be divided on the basis of mechanical layering into the lithosphere and asthenosphere (Fig. 1.3). Mechanical layering refers to the flow properties of the material, rather than its compositional properties.

The lithosphere, which includes the crust and the uppermost part of the mantle is relatively cool, and so acts in a rigid solid way and forms the lithospheric plates described below (Plate Tectonics).

The asthenosphere acts like a viscous fluid. This is because the part of the upper mantle close to the lithosphere/ asthenosphere boundary is at a temperature of about 1300^0 C, which is close to the melting point of the material. Localised partial melting in, or just below, the lithosphere causes the rise of magma to form igneous plutons within the crust or volcanoes at the surface. The lithospheric plates essentially 'float' on the semi-solid, but relatively thin, mobile layer of asthenosphere (Fig. 1.3).

Seismological techniques are used to recognise the boundaries between the different layers. When an earthquake happens, shockwaves travel out from the position within the Earth's crust where it originates (the focus) and are picked up at monitoring stations around the world. These shockwaves arrive at different times according to the type of shock wave and where the stations are situated (Fig. 1.4). The location of the earthquake focus and epicentre (point on the Earth's surface above the focus) can be calculated by using the data collected from at least three sites (triangulation).

Some shockwaves travel around the Earth's surface (Surface waves) while others travel down through the crust and mantle (Primary or Compressional Waves (P) and Secondary or Shear waves (S) - Figs 1.4, 1.5). P waves can travel through solids and liquids while S waves can only travel through solids, as liquids cannot be sheared, as they have no shape of their own, but fill whatever shape they are contained in. P waves also move more quickly than S waves.

With P waves, sometimes known as pressure waves, particles vibrate in the direction of propagation, like a coil spring, which alternately compresses and expands in the same direction (Fig.1.5). Particles in S waves, however, vibrate perpendicular to the direction of propagation, up and down in a sine curve, like when a rope is shaken (Fig. 1.5).

As no S waves arrive at the opposite side of the Earth to where an earthquake was generated (Fig. 1.4), we conclude that the Earth's outer core is molten. P waves travelling through the outer core, however, transform some of this energy into S waves when passing through the inner core, implying that it is solid.

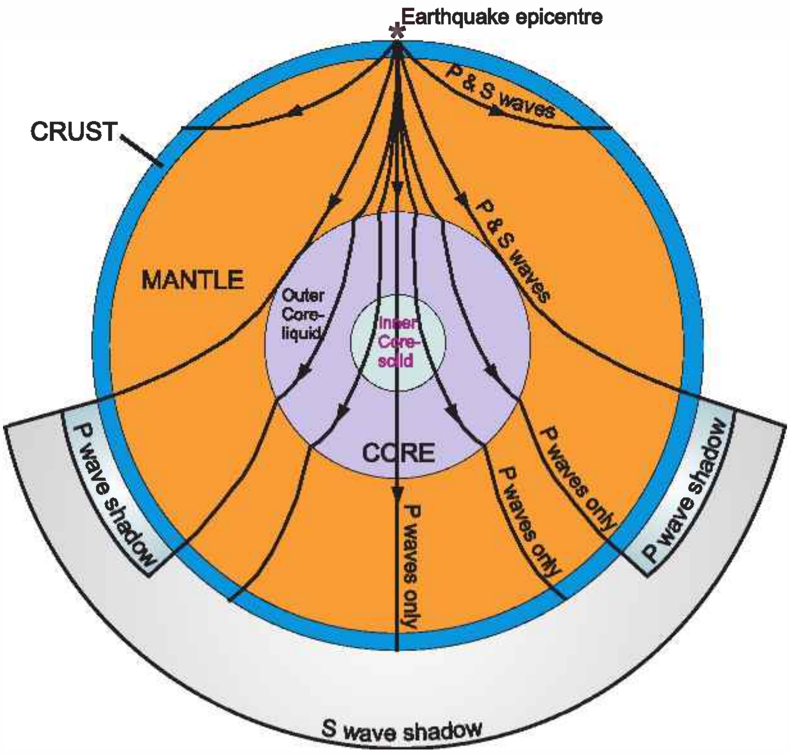

Figure 1.4 *How seismic waves identify the boundaries of the crust, mantle and core*

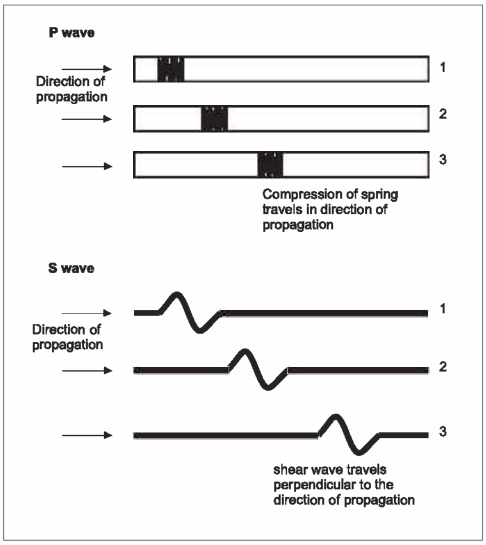

Figure 1.5 *S waves and P waves*

1.2.2 PLATE TECTONIC THEORY

The Theory of Plate Tectonics was largely developed in the 1960s by a number of geologists working independently in different countries. Their pooled ideas were to produce the fully-fledged theory. Controversial at the time, it has now been accepted with a huge body of data collected in support of it. It is now the unifying theory of geology, explaining how the Earth works in much the same way as Darwin's Theory of Evolution has influenced the biological sciences. Two important forerunners of the theory, which are incorporated into it, are the theories of Continental Drift and Sea-floor Spreading.

1.2.2.1 CONTINENTAL DRIFT

Leonardo da Vinci (1452 - 1519) wondered about the American and African continents having broken apart based on their shape and Sir Francis Bacon noted in 1620 that the continents of South America and Africa would fit together if the Atlantic Ocean were removed and commented that it was no mere accident.

In 1912 a German meteorologist and geologist, Alfred Wegener (1880 - 1930), again observed that if you moved the west coast of Africa and the east coast of South America together on a map, they fitted along with Antarctica India and Australia (see Figure 12.1), as though at some time in the past they had all been joined together. Wegener noted that terrestrial plant fossils of the same age, found in places such as South America, South Africa and Antarctica were quite similar and yet were now separated by thousands of miles of ocean. He also noticed that rock sequences close in age were of similar rock types in Africa and South America and that there was evidence for a glaciation some 300 million years ago in rocks as far apart as South America, South Africa and India.

He deduced that all the continents had drifted apart from a single supercontinent he called Pangaea (meaning all lands, in Greek). Pangaea (Fig. 11.1) began to separate into two supercontinents during the Triassic Period (250 - 203 million years ago, section 11.3). These continents were named Eurasia (northern hemisphere) and Gondwana (southern hemisphere) (Fig. 12.1).

Wegener went on to propound his theory of Continental Drift. His observations and theory were largely ignored at the time. Wegener and many other geologists after him could not find a satisfactory driver for the movement of the continents.

1.2.2.2 SEAFLOOR SPREADING, CONSTRUCTIVE AND DESTRUCTIVE PLATE BOUNDARIES

In 1959 American geologist Harry Hess of Princeton University, who had been studying the ocean ridges and troughs, informally presented his hypothesis of seafloor spreading (later published in 1962). He proposed that rock (oceanic crust) was created at the mid-ocean ridges from magma welling up from the mantle. The new rock gradually spread out either side of the ridge and was pushed towards the ocean trenches at the other side of the ocean where it disappeared down into the trench and was consumed.

This theory provided an explanation for the drift of continents, which were carried along by the spreading ocean crust. The idea was given further credence in 1963 when British geologists Fred Vine and Drummond Matthews of Cambridge University published the Vine-Matthews Hypothesis. They observed that the seafloor had stripes of oceanic crust which showed alternate magnetic polarity away from the mid-ocean ridge. They postulated that the molten magma welling up at the mid-ocean ridge recorded the direction of polarity of the Earth's magnetic field as it cooled. This was confirmed over the following years and provided the proof for constructive plate boundaries, where two plates move apart by the addition of magma injected at the mid-oceanic ridge, produced by melting of the mantle due to rising convection currents.

This theory also explained why sediments on the ocean floor were all relatively young. The oldest marine sedimentary rocks have been dated as more than 3 billion years old by radiometric methods (see Study Box 2.2), but the oldest sediments on the ocean floor are no more than about 200 million years old. The age of the ocean sediments gets older the further they are from the mid-ocean ridge and are eventually consumed when plates are destroyed at the other side of the ocean in a subduction zone, or Benioff Zone. This is named after American seismologist Hugo Benioff. Here the oceanic plate descends into the ocean trench and is carried down into the upper mantle where partial melting takes place giving rise to a line of volcanoes along the edge of the ocean (the 'Ring of Fire' - see Study Box 4.1). Subduction, due to the force of gravity acting on denser cooler oceanic crust descending down a Benioff Zone, is now thought to be the main driving force for plate movement rather than pushing apart at the mid-ocean ridge.

1.2.2.3 CONTINENTAL COLLISION

Where two continents collide, neither is subducted as the continental material is too light and resists downward movement. Instead the crust buckles and mountains are forced up. The Himalayas are a good example where the Indian plate is pushing against the Eurasian plate and continuing to force up the mountains.

1.2.2.4 HOTSPOTS

In the same year as Vine and Matthews explained magnetic striping of the oceanic crust, a Canadian geophysicist, J. Tuzo Wilson at Toronto University, developed another concept of great importance to the Plate Tectonic Theory. He suggested that the volcanic islands of Hawaii and other volcanic island chains were formed because the plate, on which they were sitting, had moved over a stationary hotspot beneath the plate. A hot spot is thought to be due to a plume of hot molten material rising through the mantle like smoke from a chimney. Mantle plumes are thought to help drive convection currents in the mantle. As the plate moved so a new volcano appeared above the hotspot and eventually a line of extinct volcanoes developed. Another hotspot is presumed to exist under Yellowstone National Park, Wyoming, where there are more than 10,000 hot springs, mudpots, pools and geysers including 'Old Faithful' within the old calderas (large volcanic craters). The hotspot theory explained why volcanoes are found thousands of kilometres from a plate boundary. Recently, American geologist Don Anderson and British geologist Gillian Foulger and others have suggested that the volcanoes in Hawaii and similar features are due to cracks in tectonic plates rather than mantle plumes. Thus the debate over the mechanisms of plate tectonics continues.

1.2.2.5 TRANSFORM PLATE BOUNDARIES

In 1965 Wilson published another seminal paper proposing that there was a third type of plate boundary, a transform boundary, where two plates slide past each other with neither being consumed, as happens along the San Andreas Fault in California (see Study Box 2.1).

The combination of these theories and hypotheses has come to be known as the Theory of Plate Tectonics. It is developed in relation to Ireland in the later chapters in this book.

1.3 THE ROCK CYCLE

All rocks fall into one of three categories: - igneous, sedimentary, or metamorphic. Igneous rocks are injected into the Earth's crust as molten magma. The magma either cools to form bodies of rock (e.g. granite) within the continental crust, or it reaches the surface on the land or ocean floor where it forms volcanoes.

The erosion of rocks produces sediment. Erosion products may eventually be deposited in layers called beds, forming a stack of sediment, with the oldest sediment at the base. As these beds become buried under younger sediments they are lithified by a combination of processes such as compaction, due to the weight of overlying sediment, and cementation, arising from fluids with dissolved salts flowing through the sediment to form sedimentary rocks.

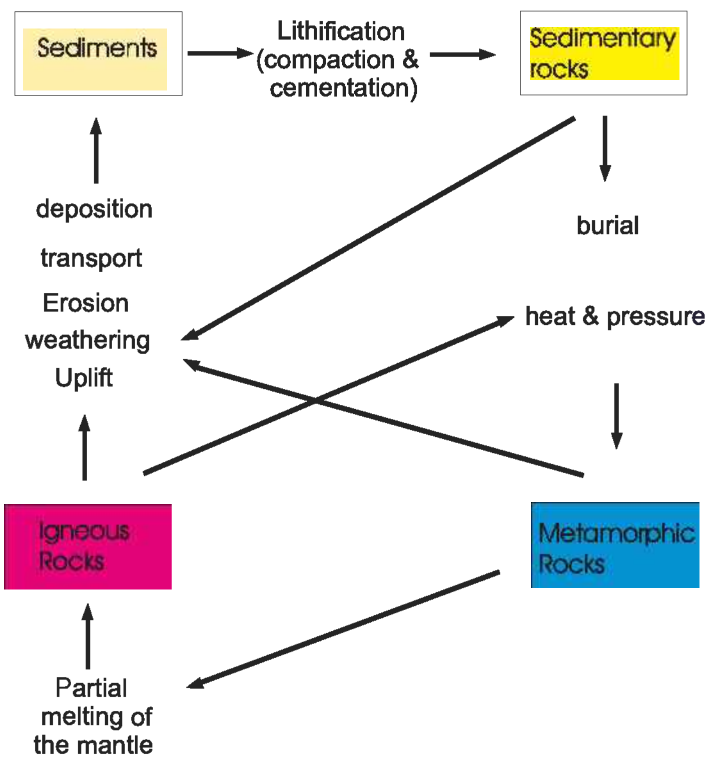

Figure 1.6 *The Tectonic Rock Cycle*

Metamorphic rocks originate from igneous or sedimentary rocks. Metamorphic rocks are also sometimes re-metamorphosed. Metamorphic rocks result from recrystallisation due to the pressure and heat generated when rocks are buried deep within the crust, or are formed locally in a zone around an igneous intrusion due to the heating effect.

The formation of igneous, sedimentary and metamorphic rocks is an integral part of the plate tectonic processes of seafloor spreading, subduction and continental collision. The heat dissipated from the Earth's molten interior drives this plate tectonic rock cycle.

The processes of weathering and erosion follow the raising of a mountain range like the Himalayas by continental collision. These processes over time will reduce the mountains to much lower levels as the detritus is carried to the sea and deposited as sediments later to be lithified into sedimentary rocks. These sedimentary rocks in turn may be buried deep within the crust and metamorphosed. They may be carried down a subduction zone and the metamorphosed rocks partially melted to be re-injected into the crust as igneous rocks. Thus the tectonic rock cycle goes full circle (Fig. 1.6).

It is a fundamental geological principle that **minerals and rocks are only stable under the conditions at which they are formed**. Change the conditions, such as, pressure and temperature, and the rocks may change into new rock types. This will be illustrated in the section below on rock classification and common rock types.

It must be remembered that sediments and rocks have often been recycled a number of times in geological history. Minerals such as quartz, which are resistant to erosion, may have survived recycling several times in the geological record.

1.4. ROCK CLASSIFICATION

1.4.1 IGNEOUS ROCKS

Igneous rocks are classified according to their grain size and mineral composition (Table 1.1).

Large magma bodies deep within the crust cool slowly. The constituent minerals are able to grow crystals and form a coarse-grained rock that is called plutonic. Magma that reaches the surface cools rapidly in the air or underwater to form volcanic, or extrusive rocks. The resulting rocks have smaller crystals and are described as fine-grained. Igneous rocks formed at intermediate depths, like dykes (vertical sheets) and sills (horizontal sheets) are called hypabyssal and are medium-grained.

Mineral Composition	Acid (Felsic)		Intermediate		Basic (Mafic)
	Oversaturated (essential quartz)		Saturated (no essential quartz)		
	Mainly micas (muscovite & biotite)		biotite, amphibole, pyroxene		mainly pyroxene
	Mainly Orthoclase Feldspar	Mainly Plagioclase Feldspar	Mainly Orthoclase Feldspar	Plagioclase Feldspar	
Fine-grained	RHYOLITE	DACITE	TRACHYTE	ANDESITE	BASALT
Medium-grained	MICROGRANITE	MICROGRANO-DIORITE	MICROSYENITE	MICRODIORITE	DOLERITE
Coarse-grained	GRANITE	GRANODIORITE	SYENITE	DIORITE	GABBRO
Av. silica %	72	66	59	57	48
Specific gravity	2.4-2.7		2.8		2.9

Table 1.1 *Simplified Igneous Rock Classification*

Igneous rocks are also differentiated into felsic (acid), intermediate, and mafic (basic) types according to their mineral composition, based on the percentage of silica contained in them (Table 1.1). Silica (SiO_2) is a constituent of many rock-forming minerals but also occurs on its own as the mineral quartz. 'Acid' rocks are those that contain quartz as a separate mineral. On the other hand 'basic' rocks do not contain quartz as a mineral but contain silica bound up in other minerals such as plagioclase feldspar. There is an increase in rock density (specific gravity - SG) from acid to basic that reflects a decreasing proportion of the lighter silica and an increase in the denser ferro-magnesian (mafic) minerals such as the pyroxenes and amphiboles.

The 'acid' rocks are light in colour. 'Basic' rocks are typically darker coloured because they include the green or black mafic minerals.

The feldspars are one of the most common groups of minerals in igneous rocks. They are complex aluminium-rich silicates in combination with other elements such as potassium, sodium and calcium. They are divided into two main types – orthoclase and plagioclase. Orthoclase is an alkali feldspar rich in potassium ($KAlSi_3O_8$) that is found in granite and its volcanic equivalent rhyolite. Plagioclase feldspars form a continuous series showing a gradual variation in chemical composition between two end members, sodium rich albite ($NaAlSi_3O_8$) and calcium rich anorthite ($CaAl_2Si_2O_8$).

Some of the rock types shown in Table 1.1 are not very common in Ireland. The most common plutonic rocks in Ireland are granite, granodiorite and gabbro. The most common volcanic rocks are basalt and rhyolite. Dolerite is often found in dykes and sills.

The more common igneous rocks in Ireland are described below.

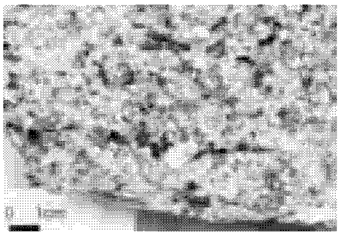

Figure 1.7 *Granite*

Granite (Fig. 1.7) is found extensively in Counties Wicklow, Galway, Donegal, and Down. Granite is often used loosely as a term to cover quite a variety of rocks in the same family. Irish granites typically comprise quartz, both alkali and plagioclase feldspars, and muscovite and biotite micas, bound together as a coarse-grained granular fabric (monzogranite, to give it its proper name). Quartz (SiO_2) is usually colourless or white. The feldspar is also white or pink. Micas are minerals with a flat planar habit and form the white shiny flecks (muscovite) and the dark coloured mineral flecks (biotite) in the granite. Sometimes other dark ferro-magnesian (mafic) minerals such as hornblende are found in granite.

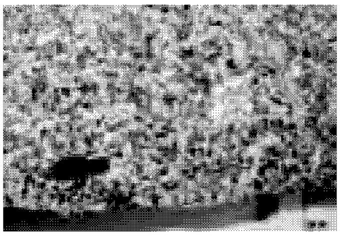

Figure 1.8 *Granodiorite*

Granodiorite (Fig. 1.8) differs from granite in the type of feldspar it contains and typically has less silica and more mafics, but otherwise is very similar. Granodiorite contains plagioclase feldspar whereas granite, *sensu stricto,* contains more orthoclase feldspar. Some of the Donegal and Wicklow 'granite' is in fact granodiorite. Other Granodiorites are the Newry and Ox Mountains Granodiorites.

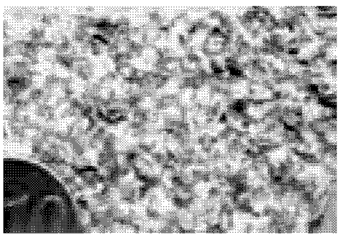

Figure 1.9 *Gabbro*

Gabbro (Fig. 1.9) is also a plutonic rock composed of calcium rich plagioclase feldspar and the dark mafic pyroxene mineral augite and /or the amphibole mineral hornblende. Sometimes, in addition, another green mineral olivine is present.

At Killala, Co. Mayo, gabbro forms a giant dyke 400 m wide and is of Tertiary age. A large area of Ordovician gabbro occurs in Connemara. The Connemara gabbros are metamorphosed, although they retain their gabbroic texture, and therefore should be called metagabbros. Gabbro is the plutonic equivalent of basalt and typically does not contain quartz.

Figure 1.10 *Rhyolite*

Rhyolite (Fig. 1.10) is similar in chemical composition to granite but is a volcanic rock. Rhyolitic magma is very viscous (because of the high silica content) and inclined to explode violently from the vent. Rhyolites are found extensively within the Ordovician volcanics of southeast Ireland.

Figure 1.11 Basalt

Basalt (Fig. 1.11) is the most common volcanic rock in Ireland and is the chemical equivalent of gabbro (Table 1.1). Plagioclase feldspar is the most common mineral constituent together with the pyroxene augite and minor quantities of minerals like magnetite and olivine. Basalt is typically extruded quietly, as the magma is runnier and forms extensive flows. The Carboniferous volcanics in Co. Limerick, near Pallas Grean, are also basaltic in character but as the activity began to wane so the composition of the magma changed to a more viscous type called **trachyte.** A small intrusion of **syenite,** a distinctive pink rock containing coarse-grained feldspar crystals, the chemical equivalent of trachyte, is also found nearby at Knockderc.

Figure 1.12 Andesite

Andesites, (Fig. 1.12) of Ordovician age are found in northeast Leinster at Balbriggan and at the Chair of Kildare where they are associated with island arc volcanism (see chapter 4). They are an intermediate volcanic rock containing sodium and calcium rich plagioclase feldspars.

Figure 1.13 Dolerite

Dolerite (Fig. 1.13) is the hypabyssal equivalent of basalt and forms dykes, sills and volcanic plugs, emplaced high in the crust. Dolerite sills and swarms of dykes were intruded during the Tertiary and can be found from Antrim to Kerry.

1.4.2 SEDIMENTARY ROCKS

Sedimentary rocks are divided into three main groups, clastic, organic, and chemical (Table 1.2). **Clastic** rocks are the insoluble products of erosion of older rocks, which are deposited in horizontal beds, by alluvial, marine or aeolian processes. **Organic** rocks include limestone and coal and are the result of accumulations of the remains of dead calcareous animals on the seabed (limestones) and the remains of plants (coal). **Chemical** rocks, such as rock salt and gypsum, form in layers in arid climates through the evaporation of seawater or from salts dissolved in rivers draining into internal basins.

SEDIMENTARY CLASSIFICATION	MAIN ROCK TYPES
CLASTIC	conglomerate breccia sandstone arkose sandstone greywacke siltstone mudstone
ORGANIC	limestone dolomite lignite coal
CHEMICAL (Evaporitic)	rock salt gypsum anhydrite

Table 1.2 Classification of Sedimentary rocks

Sedimentary basins are areas where sediment accumulates and subsides to form thick sequences of sedimentary rocks. They may be formed in the marine environment or on continents as internal drainage basins like the Great Salt Lake Basin of Utah. Sometimes, if subsidence exceeds the input of sediment, they are areas of deep-water, but if the sediment input keeps up with subsidence, then there may be little topographic expression of the basin at the surface.

1.4.2.1 CLASTIC ROCKS

Diameter (mm)	Sediment Name	Rock type
>256	Boulder	Conglomerate/breccia
64-256	Cobble	Conglomerate/breccia
2-64	pebble – granule	Conglomerate/breccia
0.625-2	Sand	sandstone
0.005-0.625	Silt	siltstone
<0.005	Clay	shale/mudstone

Table 1.3 *Grain-size classification, modified after Wentworth*

Sand, silt, clay and their rock equivalents, are defined according to grain size (Table 1.3)

Figure 1.14 *Conglomerate*

Conglomerates (Fig. 1.14) are very coarse-grained and are common in the Devonian rocks of Ireland. The clasts in conglomerates are usually rounded and sub-spherical in shape as a result of erosion of the clast edges when transported.

Figure 1.15 *Breccia*

Breccias (Fig. 1.15) are the grain size equivalents of conglomerates but are made up of angular and un-rounded clasts, indicative that the clasts have not travelled far. They are typical of alluvial fans and screes.

Figure 1.16 *Sandstone*

Sandstones (Fig. 1.16) are often made up of quartz grains (SiO_2), that are resistant to erosion, and cement. Sometimes other minerals may be included in smaller quantities such as feldspar. A feldspathic sandstone is called an **arkose**. The cement that binds the sand grains together is often also quartz, but may also be carbonate ($CaCO_3$) or a combination of minerals. The cement occupies the pore spaces between the grains.

Some sandstones can be loosely cemented leaving some of the pore space empty, or filled with water, gas or oil. However, this is rare in Irish sandstones, which are cemented tightly together. Gas has been discovered from the Drumkeeran Sandstone (Carboniferous) in Co. Cavan but has not yet been exploited. The porosity and permeability of this sandstone reservoir, however, is low, making it a prospect of marginal commercial significance.

Figure 1.17 Greywacke

Greywackes (Fig. 1.17) are impure sandstones. They are aggregates of sharply angular fragments of every size between sand and fine gravel, often in a matrix of mud. Sometimes there is so much mud that the sand particles float in the mud (wacke). The grains have often been derived from a wide variety of parent rocks and were deposited rapidly by turbidity currents (see Study Box 5.1).

Figure 1.18 Siltstone

Siltstone (Fig. 1.18) is a rock type common in the Devonian where it is often found as silty sandstone or silty mudstone typical of alluvial floodplains. It is quite difficult in the field to tell the grain size difference between these extremes.

Figure 1.19 Shale

Shale and mudstone (Fig. 1.19) are very fine-grained and, as well as quartz, contain clay minerals and often some fine organic material. Shale is a mudstone that splits readily along the plane of the bedding due to the alignment of platy clay minerals. Shales are very common in the Devonian and Carboniferous.

1.4.2.2 ORGANIC ROCKS

Figure 1.20 Limestone

Limestone (Fig. 1.20) is the most common rock underlying the unconsolidated surface deposits in Ireland. It is composed mostly of the disseminated fragments of the shells of calcareous ($CaCO_3$) animals that lived on or above the seafloor (see Study Box 9.1). The fragments are usually cemented by calcium carbonate precipitated from solution in the buried sediment. Limestones are typically found where there is little clastic sediment entering the sea to dilute the build up of fossil remains. **Dolomite** ($CaMg(CO_3)_2$) is a variety of limestone usually associated with chemical changes after burial of the lithified limestone (diagenesis). Magnesium replaces some of the calcium in the limestone, which involves a volume change resulting in increased porosity. In the Carboniferous Limestone dolomitisation has altered much of the uppermost part of the Waulsortian Limestone (section 9.1) in the southeast midlands. Dolomites also form in limestones along faults which act as conduits for the magnesium rich fluids.

Figure 1.21 Coal

Lignite and Coal (Fig. 1.21) is formed from thick deposits of vegetation deposited as peat in hot wet tropical swampy conditions. For lignite or coal to form the vegetation must be deposited where there is little oxygen so that decay is prevented and there is rapid subsidence to allow a thick sequence to build up. A bog or swamp is the ideal environment. Finally the peat deposit has to be buried under thick sediments so that it can be compacted and further changes involving burial and heat can take place. Lignite is a soft brown coal where some of the original plant structures remain but some of the 'volatiles' (hydrocarbon gases) have been driven off by heating to 40°C. Bituminous coal is a hard black coal where burial has resulted in heating above 70°C. Above 170°C bituminous coal is transformed into anthracite. At each stage from peat to anthracite, the calorific value of the fuel increases.

Lignite is found in the Tertiary Lough Neagh sequence (section 15.2). Coals are found in the Upper Carboniferous delta sequences (See Study Box 10.1) and in Leinster are of anthracite grade.

1.4.2.3 CHEMICAL (EVAPORITIC) ROCKS

In arid and semi-arid environments, salts dissolved in river water may be deposited in layers in playa lakes by evaporation of the water. Playa lakes are lakes in internal drainage basins with no outlet to the sea, like the Great Salt Lake in Utah. Evaporation may also result in precipitation of salts to form a crust in the supra-tidal area (sabkha) of shallow tropical seas like the Persian Gulf. (see Study Box 11.1)

Figure 1.22 Gypsum

The common evaporites are **rock salt** (mined from Triassic rocks in Co. Antrim), **gypsum** (Fig. 1.22) and **anhydrite** (Kingscourt, Co. Cavan) (see Study Box 11.1). Dolomite sometimes precipitates under these conditions as well.

1.4.3 METAMORPHIC ROCKS

There are three types of metamorphism; these are thermal (contact), dynamic, and regional metamorphism. These processes are described first and then a description of the common metamorphic rock types follows.

1.4.3.1 THERMAL METAMORPHISM

Thermal metamorphism is relatively local in extent and is related to the heating effect of an igneous intrusion on the surrounding rocks. The heat alters the mineralogy of the surrounding rocks, in the solid state, to form new metamorphic minerals. Which minerals are formed depends on the original chemical composition of the rocks and the temperature reached. It is common to find a halo (or "aureole") around an igneous intrusion with higher temperature metamorphic minerals close to the intrusion grading away to lower temperature minerals until unaltered rock is reached. Metamorphic halos are found, for example, in the Ordovician rocks surrounding the Leinster Granite. The granite was intruded during the Devonian Period.

14.3.2 DYNAMIC METAMORPHISM

Dynamic metamorphism is due to tectonic pressure. This leads to physical and mineralogical changes in the original rock and is accompanied by some heating due to friction. When one part of the Earth's crust moves in relation to another, as along a fault or shear zone, the rock is broken into smaller pieces in a process called cataclasis. The products of this process depend on the depth at which faulting takes place. Greater depth and consequent higher temperatures and load pressure may give rise to ductile (plastic) deformation. At shallow levels in the crust faulting produces fault breccia. At deeper levels where temperatures and load pressures are higher ductile deformation gives rise to mylonite. Mylonite is a rock consisting of streaky lens shaped fragments in a fine-grained matrix.

1.4.3.3 REGIONAL METAMORPHISM

Regional metamorphism (or Thermo-dynamic Metamorphism), as the name implies, covers wide areas and is part of the plate tectonic rock cycle and mountain building process. It involves burial of rocks deep in the crust with the formation of a range of new metamorphic minerals, which are formed under different temperature and pressure (stress) conditions. These conditions can be described in terms of low-grade, medium-grade, and high-grade regional metamorphism. As well as the formation of new minerals, regional metamorphism results in the development of new textures. Where unequal (differential) stresses have been applied then platy minerals will re-grow perpendicular to the maximum stress. As a result the rock may split along the plane of realigned minerals. Such a realignment of the rock fabric is called a foliation. It particularly affects fine-grained rocks such as mudstones. The changes in a mudstone with increasing metamorphic grade are outlined below (See Fig. 1.23). Regional metamorphism may be divided into: -

Low Grade - With high differential stress at fairly low temperatures clay minerals are realigned in a mudstone and a **slate** is formed. Slate contains a cleavage, that is, a plane of parting perpendicular to the direction of stress applied. This cleavage is what distinguishes a slate from shale. The parting in shale is parallel to the bedding. Bedding may still be visible at a different angle to the cleavage in a slate (Fig. 10.8).

With increasing temperature and pressure (Fig. 1.23) recrystallisation is more pronounced and clay minerals are replaced by other platy minerals such as muscovite and chlorite. The resulting rock is called a **phyllite** and has a silky feel and a distinct sheen caused by reflections from the surfaces of the muscovite.

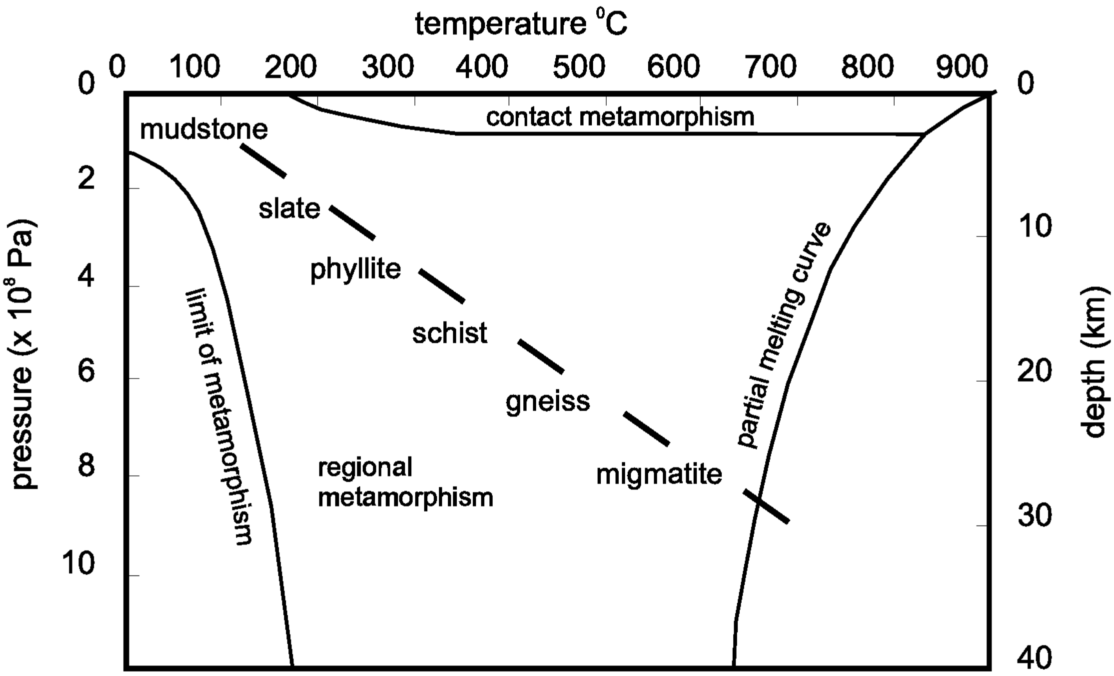

Figure 1.23 *Diagram showing the progression of metamorphic rocks produced from a mudstone with increasing temperature and pressure.*

Medium Grade - At higher temperatures, say 300 - 400°C, (Fig. 1.23) medium to coarse-grained metamorphic rocks such as **schists** are formed. Schists have a wavy foliation called a schistocity. With increasing temperature, chlorite-schists form and then mica-schists form from fine-grained rocks, with the growth of micas such as the (brown) biotite and (white) muscovite. Garnets grow at still higher temperatures. Sandstones are transformed into metamorphic rocks with a granular texture and often show a rough schistosity. Pure sandstones are metamorphosed into **quartzite**. Limestones and dolomites are metamorphosed to **marble.**

High-grade – In high-grade regional metamorphism mudstones are transformed into **gneiss**, and at temperatures close to the melting point **migmatites** form (Fig. 1.23). Gneiss has a crude banding due to segregation of the paler minerals (quartz and feldspar) from the darker mafic minerals (biotite, garnet) at higher temperatures and pressure. At even higher temperatures partial melting results in the felsic and mafic gneissose bands becoming stirred and partly mixed together to form migmatite. Further heating and migmatite begins to migrate as a melt, which involves igneous processes.

Original Sedimentary rock type	REGIONAL METAMORPHISM		
	Low Grade	Medium Grade	High Grade
Sandstone/Greywacke	quartzite/ meta-greywacke	quartzite/schist	para-gneiss
Mudstone	Slate/phyllite	mica schist	para-gneiss
Limestone/Dolomite	marble	marble	marble
Basalt	meta-basalt	amphibolite	amphibolite
Granite	meta-granite	meta-granite	ortho-gneiss

Table 1.4 *Classification of regional metamorphic rocks*

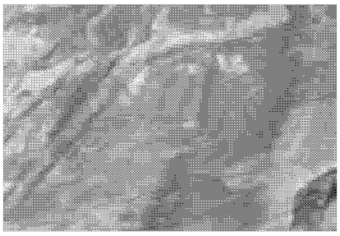

Figure 1.24 *Slate*

Slate (Fig. 1.24) is a metamorphosed mudstone, commonly found in areas of high tectonic stress such as a destructive plate margin. Mica, chlorite and quartz are the principal minerals found in slate, but their grain-size is too small to distinguish the minerals with the naked eye.

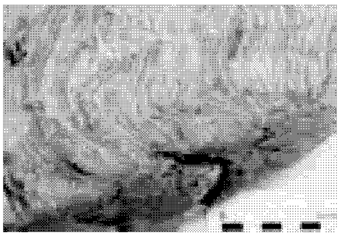

Figure 1.25 *Phyllite*

Phyllite (Fig.1.25) is formed under similar but slightly higher temperature and pressure conditions to slate. It is a fine-grained rock containing the platy mineral sericite, which gives a silky sheen. It is coarser grained than slate but finer than mica schist.

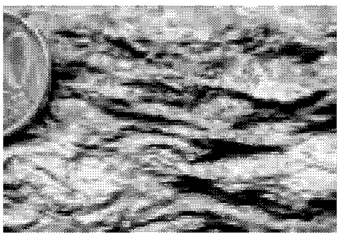

Figure 1.26 *Schist*

Schist (Fig. 1.26) is a medium to coarse-grained rock where the grains are aligned parallel to one another (schistosity). Schists are mostly made up of biotite, muscovite and quartz, but they sometimes contain other minerals such as chlorite, garnet, staurolite and kyanite. The individual mineral grains can be seen with the naked eye in contrast to phyllite.

Figure 1.27 *Gneiss*

Gneiss (Fig. 1.27) is a medium to coarse-grained rock having a granular texture and a coarse banding due to segregation of felsic and mafic minerals. Gneisses derived from igneous rocks are called *orthogneisses* and those derived from sedimentary rocks are called *paragneisses.*

Figure 1.28 *Marble*

Marble (Fig. 1.28) is a fine to coarse-grained recrystallised metamorphosed rock derived from limestone or dolomite.

Figure 1.29 Quartzite

Quartzite (Fig. 1.29) is metamorphosed recrystallised sandstone composed of 80% or more quartz. When recrystallised, the quartz grain boundaries interlock with each other like a jigsaw puzzle, but the grains are too small to see this with the naked eye. The interlocking grains make it very strong and hard to break.

Figure 1.30 Hornfels

Hornfels (Fig. 1.30) are produced most commonly adjacent to igneous intrusions by contact metamorphism. They are hard, dense granular metamorphic rocks that break into splintery fragments. Their mineral content is variable depending on the original rock type and the temperature to which the original rock was subjected.

1.4.3.4 METAMORPHIC ROCK TYPES

Metamorphic rock names are mostly related to the metamorphic fabric and the mineral composition. So a prominent mineral contained in a particular metamorphic rock is sometimes given as a prefix, for example, mica-schist, where mica minerals are common.

1.5 FOSSILS

1.5.1 WHAT IS A FOSSIL ?

From the Latin *fossilis*, meaning, "anything dug up", in the 14th century the term 'fossil' was used to describe any curious stone or strange mineral found in the ground, and was only later (17th century) confined to 'figure-stones', so-called because of their resemblance to living things. Nowadays, a fossil would be defined as the remains or trace of an organism of a past geological age, preserved in the rocks.

1.5.2 WHAT ARE THE CHANCES OF PRESERVATION ?

The fossil record represents a very small and highly biased sample of past life. The 250 thousand known fossil species of plants and animals are thought to represent less than 0.25 % of all the species that ever lived! Fourteen million living species are known today and the chances of any being fossilised are remote.

Generally, preservation is more likely to happen under water than on land, as rapid burial by soft sediment is a first requirement. After death, animals and plants sink to the sea or lakebed, and if they avoid predation by scavengers, break-up by currents, premature bacterial decay, and are quickly covered by more sediment, then fossilisation is possible.

However, chemical solution or recrystallisation can still affect a long-formed fossil, and at some later geological period, metamorphism of the rock may leave its fossils anything from distorted to obliterated.

1.5.3 WHAT IS PRESERVED ?

Rarely will the whole animal be preserved. Exceptions are the Ice Age Woolly Mammoth preserved in the frozen tundra of Siberia; and the insects trapped in amber, a fossilised resin that oozed from the trunks of Oligocene-aged (Tertiary, see Chapter 15) pine trees, for example, around the Baltic coast.

Most commonly it is the hard parts of the animal, that is, the shell, bones or teeth that are preserved. The hard parts of calcareous organisms are made up mostly of calcite (corals, echinoderms and brachiopods) and the more soluble form of calcium carbonate, aragonite (burrowing bivalves, gastropods and ammonites). Other skeletal components include opaline silica (some sponges) or a complex organic substance known as chitin (graptolites and arthropods).

1.5.4 HOW ARE THEY PRESERVED ?

During fossilisation, aragonite shells often change to calcite, this coarse recrystallisation obliterating the original shell structure. A more delicate replacement of the original mineralogy may occur by petrifaction, as minerals from percolating waters impregnate hard parts. Thus, ammonite shells in Lias clays (see Chapter 12 Jurassic) are often replaced by iron pyrites. Or, more impressively, the cell structure of fossil wood is faithfully replicated by opaline silica. The ‘fossil forest’ exposed on the Dorset coast of England at Lulworth Cove is the remains of silicified conifer tree stumps of Jurassic age.

The outline of an animal or plant composed of organic components may be preserved as a carbonised residue, following the loss of the more volatile constituents. For example, chitinous graptolites in Ordovician rocks (see Section 4.6) are frequently seen as carbonaceous films along shale bedding planes.

Percolating ground waters, which are often slightly acidic, easily dissolve already fossilised calcareous shells embedded in rock, leaving a cavity that is an external mould showing the surface markings of the shell. If the interior of the shell was filled with sediment prior to shell dissolution, an internal mould would also be formed, which can show normally hidden shell features. Internal moulds of echinoids (sea-urchins) are commonly preserved in flint (non-crystalline silica) in the Cretaceous chalk of Kent (equivalent to the Ulster White Limestone), siliceous oozes or secondary silica in solution (see Section 13.1) having infiltrated through holes in the shell before it was dissolved.

1.5.5 TRACES AND IMPRESSIONS

Indications of past life (trace fossils) are also found in the form of footprints, burrows and grazing trails (see Study Box 8.2) made by worms, bivalves and indeterminate animals. Of international importance is the Devonian trackway on Valentia Island (see Section 7.7), made by a salamander-type tetrapod walking across a wet fluvial mudplain. Its hardening prints were quickly inundated by the next sediment influx, enabling their preservation. Interweaving burrows of arthropods or gastropods cover in abundance the bedding planes of the Carboniferous Liscannor Flags in County Clare. More rare are the traces known as *Oldhamia* (Fig. 3.3), forming radiating patterns of burrows of unknown origin in the Cambrian rocks of Bray Head.

The impressions of soft-bodied animals such as jellyfish and worms, and even their internal organs are sometimes preserved within fine-grained sediments laid down in a quiet lake or similar setting. In the Jurassic Solnhofen Limestone of West Germany, beautifully detailed fossils include the bird *Archaeopteryx* complete with delicate feathers, and squid with their ink sacs still yielding ink! Ireland has its own example of exquisite fossilisation at Kiltorcan (County Kilkenny), where Devonian siltstones deposited in coastal lakes contain the remains of plants, fish and crustaceans (see Section 7.3.1.4; Fig. 7.7).

1.5.6 WHAT USE ARE FOSSILS?

Following **Darwin’s** and **Wallace’s** early evolutionary theories of ‘**phyletic gradualism**’ through **natural selection**, Gould’s ‘**punctuated equilibrium**’ (see Section 1.1) is now generally accepted as a more satisfactory mechanism for the huge numbers of species that have evolved over geological time. Evolutionary changes in past fauna and flora, known as the **fossil succession**, provide the basis for dividing the geological column into time units called **periods** (Figs 1.2, 1.31). Each period can be further subdivided into **zones**, each one characterised by a particular fossil or **fossil assemblage**.

Certain species evolved relatively rapidly into distinct new ones so that their fossils are ideal for zoning the rocks in which they occur. Many species lived in a marine habitat and enjoyed a wide geographical distribution, so that they can be used to correlate rocks of that particular age worldwide.

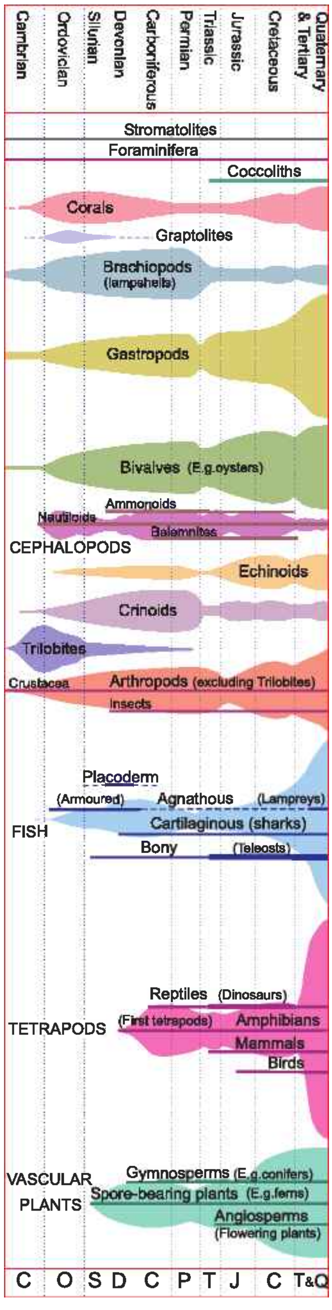

Figure 1.31 The evolution and relative diversity of different fossil groups from Cambrian times to the present.

Good examples are the planktonic graptolites of the Ordovician and Silurian periods (see Section 4.6) and the free-swimming goniatites (see Section 10.1) that are used to subdivide the Upper Carboniferous into 19 zones.

Recognition of the evolutionary sequence enables a relative dating of the rocks: for absolute dating, radiometric dating methods are employed (see Study Box 2.2).

Fossils, along with their enclosing sedimentary rocks, also make good palaeo-environmental indicators. For instance, if a species of gastropod (snail) is known to be a fresh-water type today, it is reasonable to assume that it lived in that setting in the past (see Section 1.1). Recognising past environments and the relative locations of continents and oceans through time, helps oil exploration geologists to predict where oil and gas might be found (see Section 13.3; Study Box 13.1).

Figure 1.32 Dip and Strike of inclined Carboniferous (Namurian) sandstones and mudstones, West Clare

1.6 READING THE GEOLOGICAL MAP

The geological map that accompanies this book is a simplified version of the 1:500,000 scale geological map of Ireland. In turn, that map is a summary of the 21 maps in the 1:100,000 scale regional Bedrock Map Series of the Geological Survey of Ireland. The latter series will show you in some detail the geology of your local district and is based on still more detailed unpublished six inch to the mile field sheets.

The construction of a geological map involves the recording and description of field data and then an interpretation. The detailed field sheets (usually six inch to one mile scale) record the position of data points, such as rock outcrops and boreholes, and carry a description of the rock and measurements, such as the angle of inclination (dip) of the beds and the direction of dip and direction of strike (perpendicular to the direction of dip) (Fig. 1.32). In a country like Ireland, where later unconsolidated glacial deposits cover most of the bedrock, data points may be few and far between. The interpretation of the bedrock geology attempts to show in plan (map) form the distribution of the rock formations if all the unconsolidated material was removed. It also interprets the three-dimensional folding and faulting of the rock succession. Clearly, the more data points there are available the better the accuracy of the final interpretation.

The published maps give an interpretation of the geology based on the field observations. The accuracy of this interpretation is only as good as the data collected and the skill and experience of the geologist involved. As more data are collected and new ideas are developed in geology, so revisions are made and the map changes. The new 1:500,000 scale map and the 1:1 million scale map are a considerable advance on the old 1:750,000 scale geological map of Ireland which was last updated about 30 years ago.

1.6.1 HOW ROCK UNITS COME TO LIE SIDE BY SIDE

The rock types represented on the map, like all rocks, ultimately owe their character and distribution to movement of the Earth's lithospheric plates (plate tectonics). Earth movements, during the distant geological past, have folded, faulted, uplifted and eroded the rocks so that rock units which originally were stacked one on top of the other now appear side-by-side at the surface. This can be seen in Figure 1.33, which shows a cross-section (A - B) through a simple geological map. In a borehole at B, the oldest (blue) unit would appear at the bottom of the vertical borehole, due to the dip of the rock units from left to right (northwest – southeast) - the principle of superposition of strata.

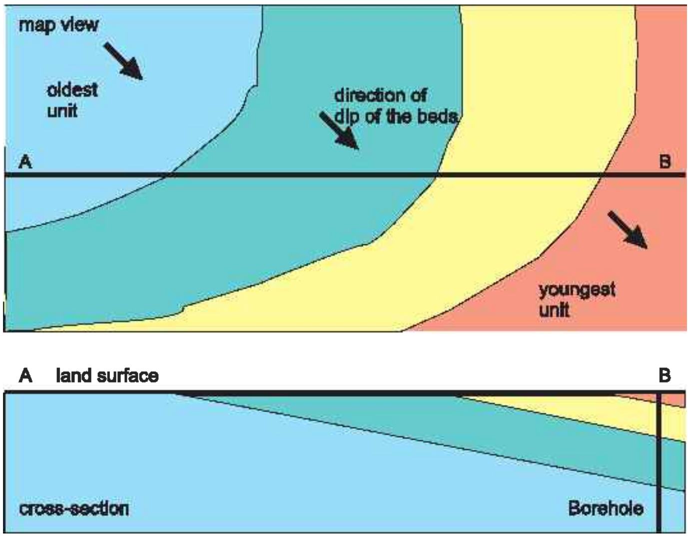

Figure 1.33 *Cross-section of a simple geological map to show the stacking of beds beneath the ground.*

1.6.2 BOUNDARIES BETWEEN ROCK UNITS

There are four principal kinds of geological boundaries: stratigraphical, unconformable, intrusive and faulted. These, however, are not distinguished on the accompanying map. **Stratigraphical** boundaries (from the Latin *stratum* – meaning a layer or bed) are the contacts between different rock units, which are often gradational rather than sharp differences between rock types. The placing of a boundary is often arbitrary, particularly where outcrops are far apart. Igneous extrusive contacts fall into the same general category but are usually 'sharp'. Intrusive rock contacts may cross-cut stratigraphical contacts.

Unconformities represent a break or gap in the rock sequence. **Unconformable** contacts often, but not always, show an angular discordance between the units, due to Earth movements and folding of the older rocks before the younger ones were deposited. For example, the Devonian Old Red Sandstone rests unconformably on older folded and eroded Silurian rocks throughout most of the country.

Figure 1.34 demonstrates an unconformity in a simple geological map. The youngest beds (5) dip to the northwest at a shallow angle and overlie the older beds (1 - 4) dipping steeply to the southeast. The contact between the youngest unit and units 2 and 3 is an angular unconformity. Unit 1, the oldest unit, is concealed beneath the youngest unit.

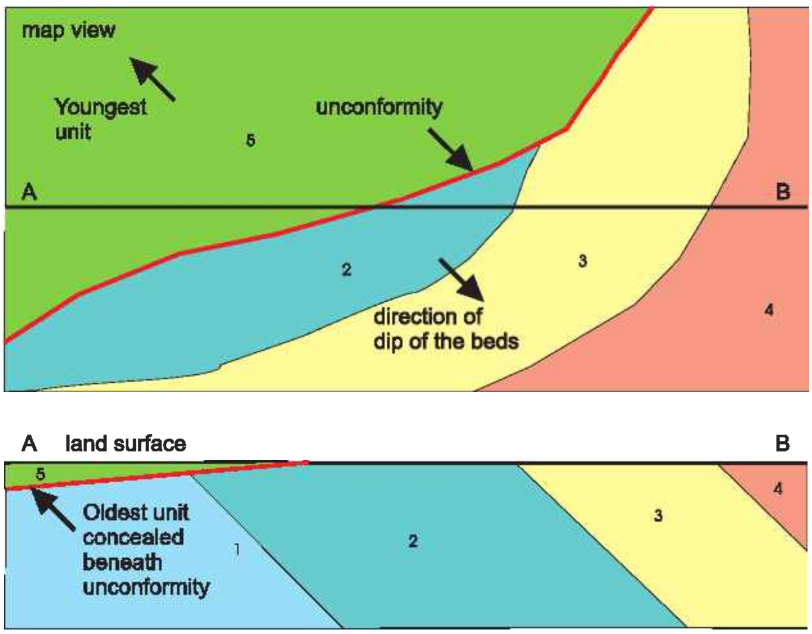

Figure 1.34 *Cross-section of a simple geological map to show the stacking of beds beneath the ground with younger beds overlying an unconformity cutting across the older beds*

Faults are fractures that displace rock sequences on either side due to pressures in the Earth's crust, often close to plate boundaries. Displacement of rocks on one side of a fault plane (the plane of fracture) relative to that on the other side may be up, down, horizontal or commonly a combination of these (oblique).

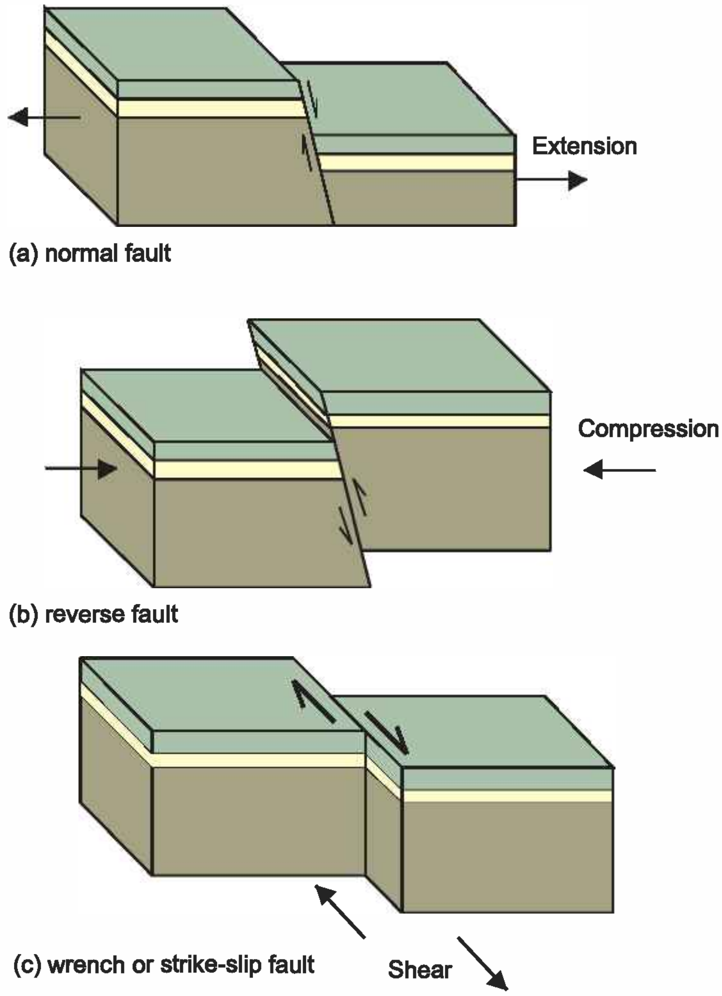

Figure 1.35 *Fault types*

Normal faults reflect stretching (extension) in the Earth's crust whereas **reverse and thrust faults** reflect squeezing (compression, shortening) (Fig. 1.35a, b). Thrusts are reverse faults where the fault plane is at a low angle. Faults where rocks slide past one another horizontally are called **wrench faults**, or '**strike-slip' faults** (Fig. 1.35c). The scale of movement on faults is extremely variable, ranging from a few metres or so, to tens, hundreds, and even thousands of kilometres. Faults are rarely directly seen in the field in Ireland, typically having been inferred on the basis of a non-matching sequence on either side, or by the absence of part of the sequence as known elsewhere. Faults may sometimes appear to be more common in areas of abundant outcrops and/or boreholes. This is a reflection of data availability, and in reality, faults are probably more common than can be identified from the typical scattering of outcrops and boreholes.

1.6.3 VIEWING THE ROCKS

If you would like a more detailed geological map of your district, then the relevant 1:100,000 scale map and explanatory booklet can be obtained from the Geological Survey of Ireland

Should you choose to visit any geological site on private land, you must obtain permission from the owner before going to the site.

1.7 GEOLOGICAL MATERIALS & THEIR USE

It may be surprising to note that most of the things we need to sustain our way of life are derived from geological materials. These geological materials may be divided into rocks, minerals, and fluids or gas contained in rocks.

We all need shelter – somewhere to live. With the exception of wood, nearly all the other materials used in constructing and fitting out a house are derived from geological materials. We will take the different parts of an ordinary house as an example of the range of Earth materials needed. We could equally well describe the Earth resources needed to construct a car or the range of materials used to construct a road, railway, or computer.

All these materials have to come from somewhere, from mines, quarries and wells in our own country, or else they must be imported from other countries. Most of the bulky materials can be derived locally but increasingly specialist materials have to be sourced in other countries.

The common materials used in construction of a house are described below. Many other minerals are used in small amounts for specialised manufactures.

Foundations: - The foundations are constructed from concrete, which is made from fine aggregates (sand), coarse aggregates (crushed rock), Portland cement (limestone, shale), and water. The sand is commonly derived from sand pits dug into glacial materials in Ireland, but may also be dredged from the sea. The coarse aggregate is quarried locally and crushed to the appropriate size (see section 9.4). The ingredients of Portland cement are also derived from local quarries, where limestone is crushed to a powder and heated with shale after which it is ground down again and a small amount of gypsum added.

Walls: - Walls are commonly constructed of concrete blocks in Ireland, but bricks (made from clay) or dimension stone (cut and dressed stone) are also used, often as facing material. Non load-bearing internal walls are made from plasterboard which is a product made from the mineral gypsum, mined at Kingscourt (see section 11.2). Internal walls are also skimmed with gypsum plaster.

Windows and doors: - Window and doorframes may be made of wood, aluminium, steel, or PVC. PVC is a product of the worldwide petrochemical industry, ultimately derived from oil (see section 13.3) and salt (see section 11.2 & 11.3). Most of these manufactured materials have to be imported into Ireland. Lintels are constructed of pre-stressed concrete that contains a steel reinforcing mesh. Rolled steel joists (RSJ) are also used to span large spaces. The raw material for steel (iron ore) is produced in many parts of the world, notably from the Hamersley Range, in Northwest Australia. Australia produces 16% of the world's iron-ore and supplies most of Asia.

Window glass is manufactured from silica sand, limestone, dolomite and soda ash. Soda ash is the trade name for sodium carbonate, a chemical refined from the mineral trona or sodium-carbonate-bearing brines (both referred to as "natural soda ash") or manufactured from chemical processes (referred to as 'synthetic soda ash') one of which uses ammonia, coke, limestone and salt. Trona is an Evaporitic mineral found for example in the Mojave Desert at Searles Lake, Trona California. Most glass is imported to Ireland, although most of the ingredients are available.

Roof: - Slate, a metamorphic rock was used traditionally for roofing. Slate quarries in east Clare and north Tipperary, near Killaloe, and in West Cork and Kerry were used locally in the past, but the majority of slate came from North Wales – The Blue Bangor Slates – which were the best slates in the world. While they are still used in restoration work, most roofing is now made of clay tiles, artificial slate or imported slate often from Spain. Sometimes corrugated galvanised iron or mineral felt may be used. The latter is another byproduct of the petrochemical industry. Aluminium or lead is used for roof flashing.

Attic insulation is commonly made from rock wool (manufactured by steam blasting and cooling molten glass), or vermiculite. Vermiculite is a phyllosilicate mineral resembling mica in appearance, which expands like popcorn on heating). Much of it is mined in South Africa (from the Palabora opencast mine in northeast Transvaal) but also significantly in China, Brazil, Zimbabwe, and the United States.

Plumbing: - Copper tubing and brass fittings (an alloy of copper and zinc) are used in the pipe work for central heating and hot and cold water systems. Gutters and drain pipes are usually now made of PVC but older properties may have cast iron pipes and gutters. The drains are now commonly made of PVC, but clay drains are common.

Electrics: - Copper and PVC are used in the manufacture of electric wiring and tungsten is used in the filaments of light bulbs. Fluorescent light tubes contain a small amount of mercury vapour. Copper was mined in Ireland at Gortdrum (Co. Tipperary) and from West Cork – notably Allihies Mine on the Beara Peninsula, in the 19th century). Mercury was also produced as a byproduct at Gortdrum. Tungsten is currently mined at Shizhuyuan Nonferrous Metals Mine in Hunan province, China which is the largest multi-mineral mine in the world,

Fittings: - Many fittings are made of non-ferrous metals such as brass and aluminium and various oil-derived plastics. Ceramic wall and floor tiles and bathroom fittings are made of clay, the common rock forming silicate mineral feldspar, and flint (a form of silica – SiO_2) commonly found in chalk rock (see section 13.1).

Driveway: - The drive may be made of poured concrete, concrete paving blocks, gravel or asphalt. Asphalt is made by binding fine-grained aggregate with bitumen, a naturally occurring hydrocarbon, now generally produced synthetically from oil. All of these products are made locally.

1.8 ENVIRONMENTAL GEOLOGY & ENGINEERING

Geologists play a vital role in helping to keep our environment clean and healthy and in helping to design and implement major infrastructural engineering projects. The role of geology is fundamental to the provision of clean water and in designing non-contaminating waste disposal facilities.

The recent (2000) EU Water Framework Directive on water quality and river basin management requires the government through local authorities to monitor and plan both surface and underground water resources. Much of this work depends on good geological maps from which groundwater geologists, with additional data from water wells and rivers, can construct county-based groundwater protection and vulnerability maps, enabling county councils to protect areas vulnerable to pollution from poor or unsuitable development. Siting waste disposal facilities in areas where possible pollution can be contained naturally, in impervious rock strata, so that aquifers are not contaminated, is a major consideration. Adherence to published Geological Survey guidelines for something as simple as the construction of a domestic septic tank can prevent unnecessary pollution of groundwater. More than 25% of all water used in Ireland comes from groundwater wells.

Knowledge of sub-surface sediments and rock types is a very necessary step in planning and designing major infrastructural projects such as dams, pipelines, tunnels, motorways and bridges. A good understanding of the geology can help prevent unnecessary disasters happening through avoidance of bad ground, or engineering the structure to suit difficult ground conditions. For example, the possibility of cavitation in soluble limestones or due to mining can be allowed for in the design of a pipeline or road so avoiding possible expensive remedial action and litigation or even death.

2 PRECAMBRIAN - ANCIENT FOUNDATIONS

Earth's oldest rocks have been recycled and 'destroyed' by the process of plate tectonics. The oldest rocks on Earth found so far are the Acasta Gneisses in northwestern Canada, which are 4.03 billion (4,030,000,000) years old. Ancient rocks exceeding 3.5 billion years in age are found on all of Earth's continents.

Ireland's Precambrian rocks extend back in time to about 1.8 billion years ago. These very old rocks have had a long and complex history, repeatedly affected by subsequent geological events, so that their origins can be difficult to decipher. All these rocks are shown simply as 'Precambrian' on the map, but it should be remembered that they represent a longer period of Earth history than all the rest of the rocks, from Cambrian to Quaternary, put together.

Precambrian rocks occur in the southeast corner of Ireland, around Rosslare, and over a larger area in the northwest, including much of Donegal, North Mayo and Connemara. These southeastern and northwestern provinces actually originated on separate continents and were brought together to form the foundations of Ireland by plate tectonic movements during the later Ordovician and Silurian Periods. There is therefore no relationship between the southeastern and northwestern Precambrian rocks and they are discussed separately below. The southeastern Precambrian rocks are collectively called the Rosslare Complex. Most of the northwestern Precambrian rocks belong to a unit called the Dalradian Supergroup, but within these are small areas of the very oldest rocks, together referred to as pre-Dalradian.

2.1 THE ROSSLARE COMPLEX

The Rosslare Complex is divided into two major units; a group of grey gneisses, coarsely crystalline metamorphic rocks that are well exposed at Kilmore Quay, and a group of dark-green metamorphosed igneous rocks called amphibolites that are seen around Rosslare Harbour and Greenore Point.

The gneisses typically have a banded appearance, in which pale-grey bands of the minerals quartz and feldspar are separated by darker bands rich in mica. These rocks are interpreted as originating as sediments, deposited as a succession of greywacke sandstones and interbedded mudstones. Several periods of metamorphism, under high temperature and pressure conditions deep in the crust, produced the present-day gneisses. In places, thin sheets of granitic composition were injected parallel to the banding in the gneisses. These suggest that particularly high temperatures caused partial melting of the sediments and re-injection of the melted rock as granite.

The metamorphosed igneous rocks are rich in a dark-green mineral called amphibole. They are the metamorphosed equivalents of gabbro and diorite. Although the relationship is not clear, these igneous rocks probably intruded the sedimentary rocks that later became gneisses.

Deformation and metamorphism of the Rosslare Complex were caused by the Cadomian Orogeny of Late Precambrian age, which also affected rocks in southern Britain and northern France. New minerals that grew in the rocks during metamorphism have been dated as 620 million years old, but the gneisses and amphibolites were both already in existence before this time and so were produced by an even earlier metamorphism.

2.2 THE DALRADIAN

Most of the Precambrian rocks of northwestern Ireland are part of a belt of metamorphic rocks, called the Dalradian Supergroup, which extends from the west of Ireland and Donegal, through Tyrone and northeast Antrim, into Scotland. The Dalradian is composed mainly of metamorphosed marine sedimentary rocks, but includes volcanic and intrusive rocks and metamorphosed glacio-marine deposits. Deposition of the youngest parts of the Dalradian sequences probably continued without break from the Precambrian into the Cambrian Period. However, the Cambrian parts are difficult to separate on the map and all Dalradian rocks are shown as Precambrian.

The story of the Dalradian starts with continental tension and crustal thinning about 800 million years ago during fragmentation of a single late Precambrian supercontinent, called Rodinia (Fig. 2.1), and formation of a basin in which the Dalradian sediments accumulated. Deposition was initially in shallow seas, but as the continent became more stretched, it rifted apart about 600 million years ago and a major new ocean, called Iapetus, gradually opened between the continental blocks of Gondwana and Laurentia. Volcanic layers and sills, the latter mainly seen in Donegal, were emplaced as a prelude to ocean opening.

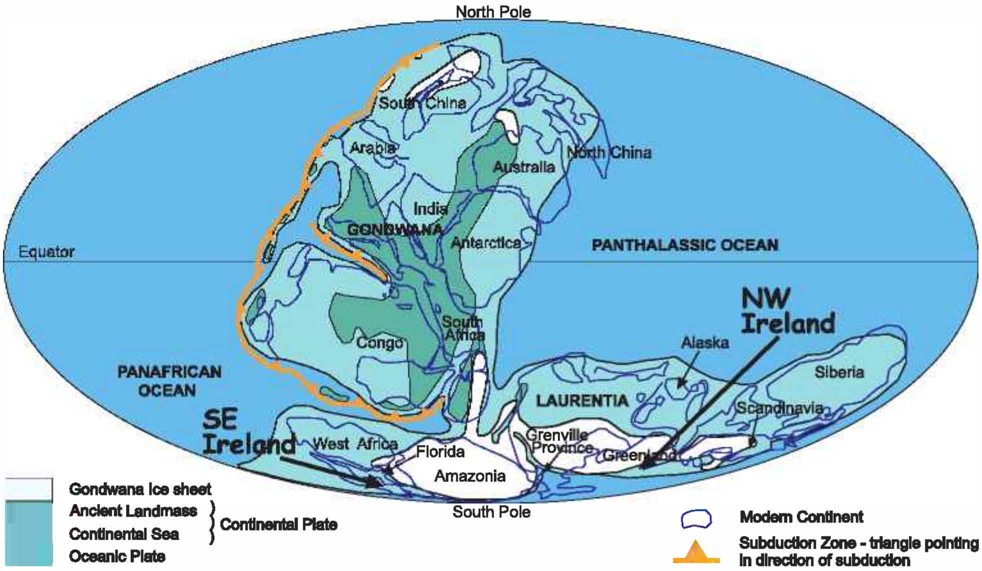

Figure. 2.1 *Plate reconstruction for late Precambrian time*

Depositional environments of the sedimentary rocks in the Dalradian Supergroup range through estuarine, intertidal, and shallow marine, to deep-water shelf and slope. A distinctive glacio-marine formation was deposited during an ice age about 720 million years ago. This ice age has been associated with the currently topical "Snowball Earth" hypothesis (see section 16.3).

In Ordovician times the Dalradian rocks were deformed into a major mountain belt by the Grampian Orogeny (section 4.1). The rocks were metamorphosed and repeated folding gave rise to complex structures. Regional-scale folding of the quartzite in the Connemara Dalradian rocks can be picked out on the map, while Fig. 2.2 shows small folds in an outcrop of Dalradian rock.

Figure 2.2 *Small-scale folds in an outcrop of Dalradian rock (lens cap in upper left for scale)*

White and pale-coloured quartzites and metamorphosed sandstones are common rock types in the Dalradian (Fig. 2.3). They are resistant to erosion, and form much of the notable high ground, such as the Twelve Bens in Connemara and the Errigal - Muckish range in Donegal. Metamorphosed mudstones and marbles (metamorphosed limestones) are other common rock types. The marbles include the well-known ornamental green marble of Connemara.

Figure 2.3 *Platy quartzites at Horn Head, Co., Donegal.*

2.3 IRELAND'S OLDEST ROCKS - PRE-DALRADIAN

The oldest rocks in Ireland occur on Inishtrahull, northeast of Malin Head, and in northwestern Co. Mayo on parts of the Mullet Peninsula and Blacksod Bay. These are coarsely-crystalline, banded gneisses produced by strong metamorphism of igneous rocks that formed approximately 1750 - 1780 million years ago. Similarly aged rocks are thought likely to lie deep below many of the younger rocks seen at the present day land surface.

The original igneous rocks were of generally granitic and gabbroic types. A complex sequence of intrusive, deformational and metamorphic events has affected these rocks during Precambrian and later orogenies.

2.4 PRECAMBRIAN LIFE

The fossil record of life spans a far greater time across the Precambrian, than from the base of the Cambrian to the present day. Presumed algal structures are known from rocks in Swaziland as old as 3500 million years, and slightly younger algal type stromatolites have been found in the African and North American continents. Very similar algal stromatolites can be seen today at Shark Bay, Western Australia (Fig. 2.4).

Figure 2.4 *Algal Stromatolites at Shark Bay, Western Australia.*

The first indications of animal life, as trace fossils of their burrows and tracks (see Study Box 8.2) are not seen until very latest Precambrian times. The Ediacaran fauna (Study Box 3.1) appears at this time, with a diversity of forms that have been compared with jellyfish, sea pens and worms.

Study Box 2.1 - Plate tectonics

The solid Earth is a dynamic planet. Internal heat generated by radioactive decay drives circulation of the rock of Earth's mantle, in turn moving the more rigid outer shell over the surface of the planet. The shell comprises a number of lithospheric plates (Fig. 1). Plates are composed of continental crust, oceanic crust or a combination of both, plus the upper part of the mantle. Movement of the plates is very slow, a few centimetres per year, but the forces are immense and account for the dynamic surface geology of Earth; earthquakes, volcanic eruptions and the construction and destruction of continents and oceans. Boundaries between adjacent plates are of three types; destructive (or convergent), constructive (or divergent) and conservative (or strike slip).

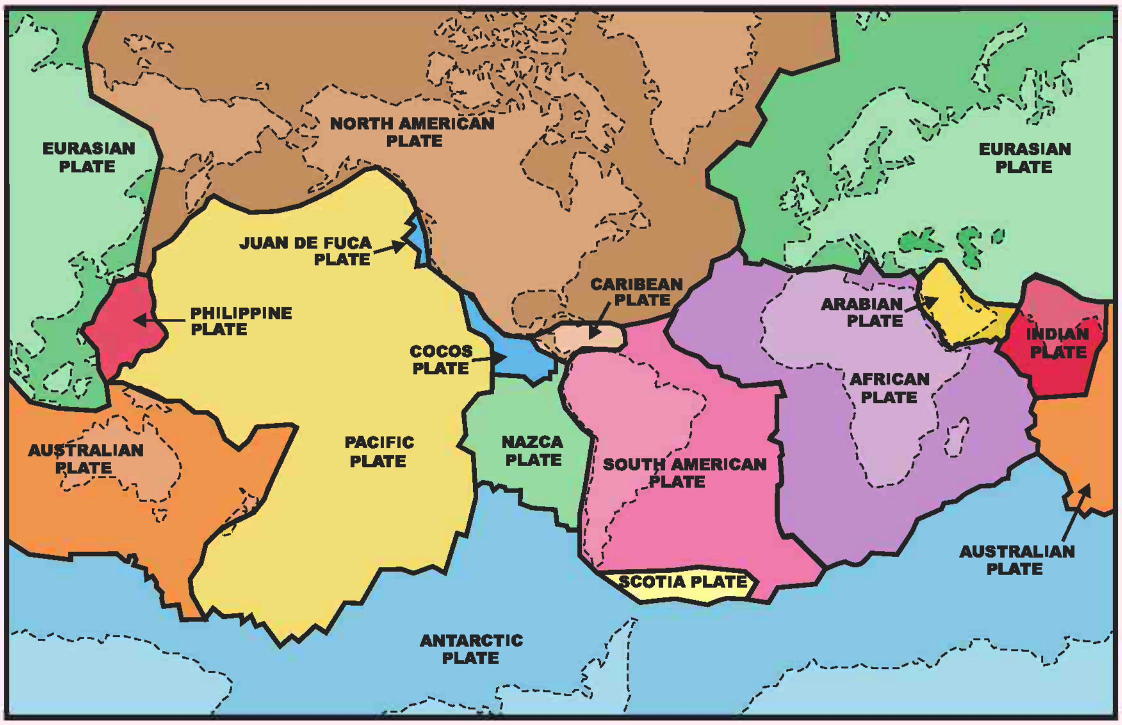

Figure 1. *Tectonic plates of the world*

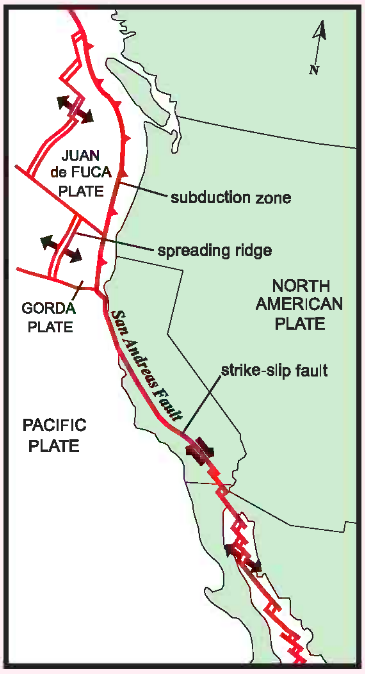

Figure 2. *The San Andreas Fault, California.*

Conservative (strike slip) plate boundaries

Some plate margins are neither constructive nor destructive; instead the plates slide horizontally past each other and are said to be conservative, i.e. crust is neither created nor destroyed. The sliding motion is far from smooth and gradual, but is episodic as stress builds up along the margin of the two plates to be suddenly released in earthquakes that can be of very large magnitude and very destructive in human terms. The San Andreas Fault in California (Fig. 2) is one such plate boundary, where the Pacific Plate is sliding northwards along the North American Plate.

As the continents move as a consequence of plate tectonic processes, they are formed and reformed in different configurations. The geological history of Ireland, as told in this book, is a history of Ireland's place amongst the evolving continents, as plate tectonics has continually modified the cycle of generation and metamorphism of rocks.

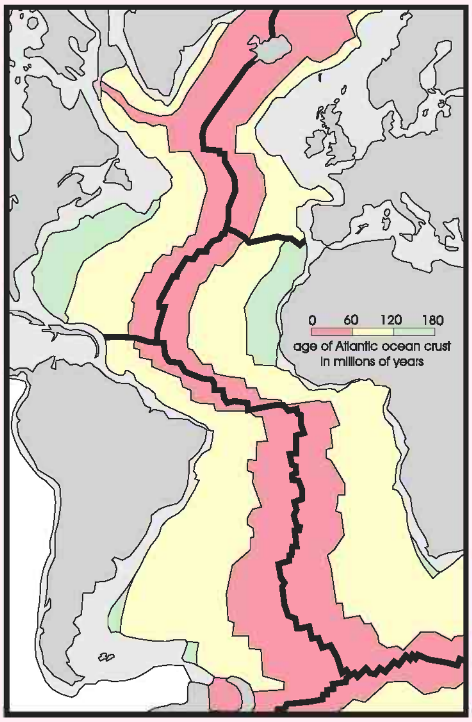

Figure 3. The Mid-Atlantic spreading ridge

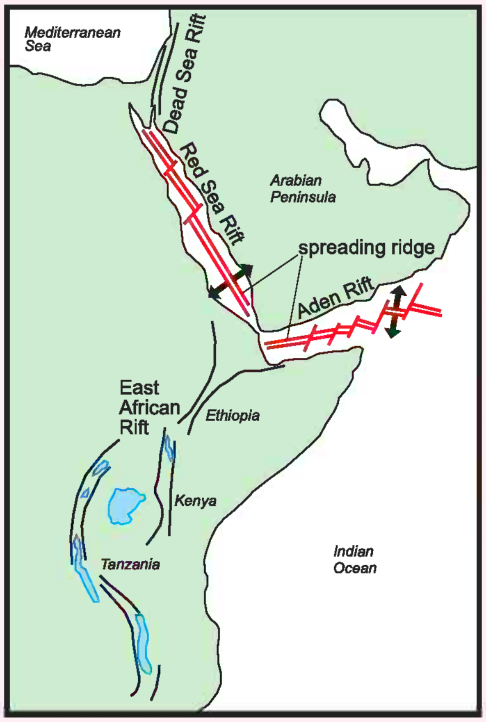

Figure 4. The Red Sea Rift

Constructive (divergent) plate boundaries

There are no gaps between the plates; at constructive margins, where plates move apart, magma wells up from the mantle to plug the gaps. Each increment of opening is filled by a sheet-like intrusion of magma that cools and crystallizes to form a dyke of igneous rock. Over millions of years new oceanic crust is formed as oceans get wider. This process is happening in today's widening Atlantic Ocean, for example, as the European and North American plates move apart at the mid-Atlantic ridge (Fig. 3).

A constructive margin can also form within a continent. At first the continental crust is extended and thinned, but eventually it is pulled apart, and new oceanic crust is formed as spreading continues. The Red Sea is a young ocean forming as the Arabian Plate pulls away from the African Plate, and the East African Rift is the continuation of this feature into the African Plate where extension has not yet led to formation of oceanic crust (Fig. 4).

Destructive (convergent) plate boundaries

At a destructive margin, where plates push together, one plate is forced down into the hot interior in a process called subduction (see Study Box 4.1). Subduction induces melting at a shallow level in the Earth's interior and results in a line of volcanoes on the overlying plate, whilst sending out the shock waves of an earthquake as plates grind past each other. A rim of volcanoes around the Pacific Ocean (the Pacific "Ring of Fire") is a result of consumption of the Pacific plate by subduction under Asia and the Americas.

When two continents collide as a result of subduction, the huge force crumples (folds) the rocks into a mountain range, for example today's Himalayas, produced by India pushing into Asia. Rocks pushed down inside a mountain range are recrystallised by the great heat and pressure. Their original minerals change in the solid state into new minerals and the rock is said to be metamorphosed. With even greater heat the rocks might melt. The molten rock then rises back up through the crust and intrudes at higher levels where it cools in bodies called plutons to crystallize as granite and related igneous rocks.

Study Box 2.2 Radiometric dating and the age of the Earth

Rocks are made up of many individual crystals, and each crystal is usually made up of at least several different chemical elements such as iron, magnesium, silicon, etc. While most of the elements in nature are stable and do not change, some elements are unstable and change from one element to another by a process called radioactive decay. The original element, called the parent element, decays to another element, called the daughter element. This happens at a known and predictable rate, called the "half-life", so that by measuring the amount of parent atoms and daughter atoms in a rock, an age can be calculated. For igneous rocks the calculated age is usually its cooling and hardening from magma or lava. For metamorphic rocks, the "age" is the heating event that caused recrystallization of the rock. Sedimentary rocks can't usually be dated directly, but their age can be constrained by dating volcanic layers within the sequence or cross-cutting igneous intrusions.

The table shows some of the more commonly used radioactive decay series used in dating rocks.

Radioactive Isotope (Parent)	Product (Daughter)	Half-Life (Years)
Samarium-147	Neodymium-143	106 billion
Rubidium-87	Strontium-87	48.8 billion
Thorium-232	Lead-208	14 billion
Uranium-238	Lead-206	4.5 billion
Potassium-40	Argon-40	1.26 billion
Uranium-235	Lead-207	0.7 billion

Table 1.

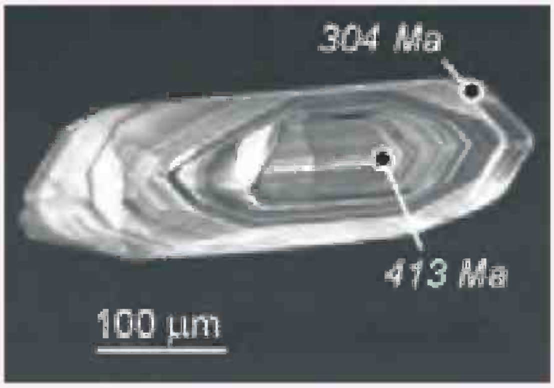

Figure 1. *Zircon crystal showing two phases of growth. A 413Ma crystal was recycled into a 304Ma magma where the crystal grew further.*

The age of the Earth cannot be determined directly from Earth's rocks because the oldest rocks have been recycled and destroyed by the process of plate tectonics (see Study Box 2.1). If there are any of Earth's primordial rocks left in their original state, they have not yet been found. The oldest rocks on Earth found so far are the Acasta Gneisses in northwestern Canada, which are 4.03 billion years old. Even older ages of as much as 4.4 billion years have been obtained for crystals of the mineral zircon that have been recycled into younger sedimentary rocks from Western Australia. The source rocks for these zircon crystals have not yet been found.

It is believed that all the bodies in the solar system were created at about the same time. Nearly all meteorites, which are pieces of asteroid, have ages around 4.56 billion years. The asteroids cooled quickly after formation and have not been remelted since, so their ages have generally not been disturbed. The ages of the meteorites are therefore a good estimate of the age of the Earth.

3 CAMBRIAN - SHELF SEAS

During the Cambrian Period, 545 – 495 million years ago, the Iapetus Ocean continued to open between Laurentia and Gondwana (Fig. 3.1). By the end of the period it had reached its maximum width of up to 5000 km, similar in scale to today's Atlantic, before beginning to close in the Ordovician.

Cambrian rocks appear on the map in three areas of east and southeast Ireland; on Howth Head to the north of Dublin Bay, around Bray Head and the Sugarloaf in northeast Wicklow, and in a band between Cahore Point and Waterford Harbour in south Wexford. All three areas comprise marine sedimentary rocks deposited on a continental shelf at the northern margin of Gondwana on the southern side of the Iapetus Ocean. The youngest parts of the mainly Precambrian Dalradian sequences (see Chapter 2) of northwestern Ireland probably extend into the Cambrian Period, but are not separated on the map.

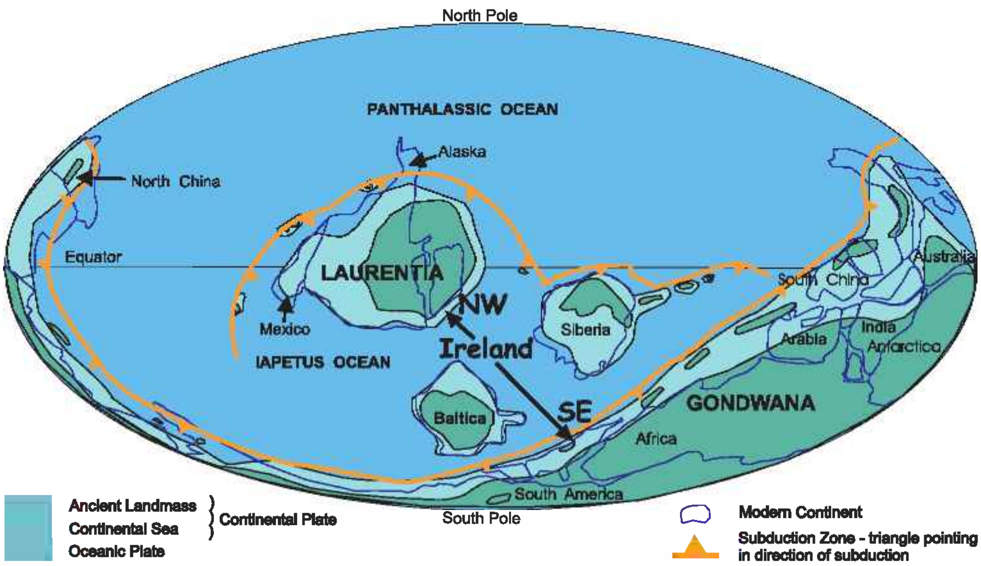

Figure 3.1 *Plate reconstruction for the late Cambrian*

3.1 BRAY AND HOWTH

The main rock types of the Cambrian are greywackes, slates and quartzites. Greywacke is a rock composed of muddy sand and sedimentary structures in the rocks indicate that they were deposited mainly by turbidity currents (see Study Box 5.1). The pure quartzite sand was produced by winnowing of mud from sand in an active sediment deposit area such as a beach. The remaining sediment was carried to a deeper site of deposition by turbidity currents. The distinctive quartzite units range in thickness from 10 m to over 100 m. The quartzites are resistant to erosion and form the high ground in the area, with pointed peaks and ridges typified by the Great and Little Sugar Loaf Mountains, prominent features in northeast Co. Wicklow (Fig. 3.2).

After the layers of sediment were built up, but before they were lithified, movements on faults caused the sediments to slump and partially mix in places. Slumped zones alternate with coherent undeformed sediments. Slumping is particularly well developed at Howth, where chaotic mixtures of rocks, varying in size from pebbles to blocks hundreds of metres across, are developed between bedded sequences.

No macrofauna has been discovered in these rocks. Microfossils have yielded an early to middle Cambrian age. Burrows and grazing trails made in the soft sediment are preserved in the rock as trace fossils, including *Oldhamia* (Fig. 3.3).

Figure 3.2 The quartzite peak of the Great Sugar Loaf, Co. Wicklow

Figure 3.3 Oldhamia

3.2 SOUTH WEXFORD

The Cambrian rocks of south Wexford occur in two distinct units. To the east of Bannow Bay the rocks are similar to those at Bray, a sequence of greywackes, mudstones and quartzites deposited predominantly by turbidity currents. In general, the resistant quartzites are massive and undeformed internally, while the weaker interbedded mudstones have a slaty cleavage. As seen at Howth, catastrophic earthquakes caused slumping of the newly deposited sediments, but rather than being broken up into chaotic mixtures, sheets of bedded sediments, up to 85 m thick, slid down slope under the influence of gravity.

Between Bannow Bay and Waterford Harbour, the Cambrian rocks comprise a finer grained association dominated by mudstones and siltstones. The very thin bedding in these rocks gives them a pinstriped appearance. The cliffs at Booley Bay (Fig. 3.4) and Dollar Bay are the best places to examine these rocks. The finer grainsize and thinner bedding of these rocks indicates that they were deposited at the far edge of turbidite sheets, in the deepest part of the Cambrian sedimentary basin. Within the thinly bedded rocks are thicker beds in which pebbles and cobbles are enclosed in a fine mud matrix. These are deposits of high-density flows of sediment called debris flows, which carry more sediment than turbidity currents and are something like underwater sediment avalanches. Black mudstones up to two metres thick, which occur sporadically throughout the succession, represent long quiescent intervals between periods of frequent (geologically speaking) earthquake activity.

Figure 3.4 Thinly bedded mudstones and siltstones at Booley Bay

3.3 CAMBRIAN LIFE

The base of the Cambrian Period is taken at the point in the geological record when marine organisms suddenly became varied and abundant, and from then onwards the fossil record is well documented. The relatively equable Cambrian climate, following the late Precambrian near-global glaciation, together with a rise in biogenic oxygen and palaeogeographic changes providing widespread shelf seas, may partly account for the marine diversification at this time. Nine invertebrate phyla are recognised in early Cambrian fossils, including the corals, molluscs, brachiopods, and echinoderms. The early forms were mostly shallow-water suspension or detritus feeders living on the seabed. The trilobites, a now extinct group of free-swimming segmented arthropods with jointed limbs, showed a rapid rise and diversification during the Cambrian. The acquisition of hard parts, from spicules to skeletal structures to shells, in contrast to the Ediacaran fauna (see below), played an important role in the preservation of marine animals as fossils. Skeletal development is thought to have provided an evolutionary advantage as a protection against predators. At first, the hard parts were made up of chitino-phosphatic minerals, but later in the Cambrian calcium carbonate was by far the commonest means of tissue mineralisation.

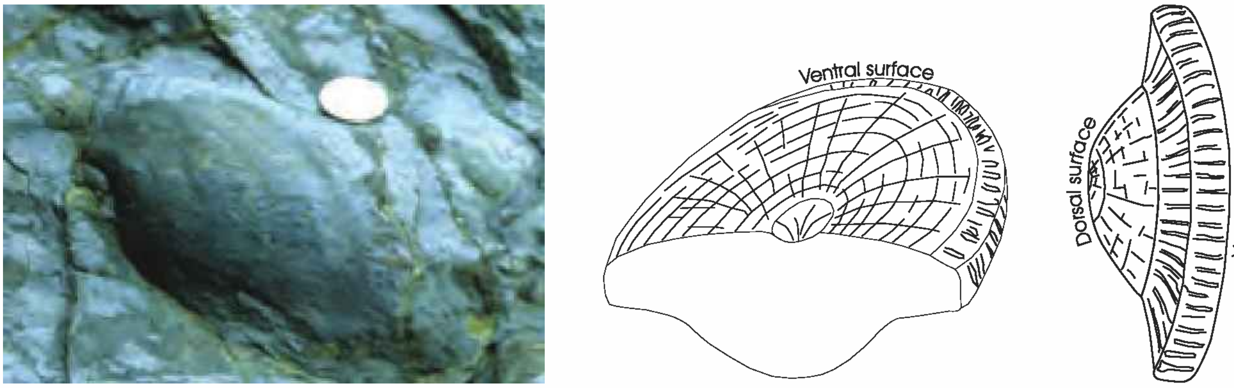

Figure 3.5 *Ediacaran fossil from Booley Bay, Co. Wexford.*

The mudstones and siltstones at Booley Bay contain rare fossils that have been attributed to a group of animals called the Ediacaran fauna (Study Box 3.1). This group of fossils is known from a number of places around the world in rocks dating from the end of the Precambrian and the start of the Cambrian Period. This is the time in Earth's history when multicellular organisms with hard shells first appeared. Independent dating using microfossils shows that the Booley Bay fossils are the youngest suggested example of Ediacaran fauna in the world (about 500 million years old, from the latest part of the Cambrian). The fossils from Booley Bay (Fig. 3.5) are of disc shaped organisms, up to 200 mm across, that resembled jellyfish but with a more rigid outer structure. These fossils are unique in Irish geology, and of international importance.

Study Box 3.1 - Early fossils - The Ediacaran fauna

The Ediacaran fauna is a distinctive assemblage of large organisms that appear in the fossil record towards the end of the Precambrian. The name derives from Ediacara in the Flinders Ranges of South Australia, where particularly good assemblages of the fossils are found. The fauna consists of soft-bodied organisms, which are typically preserved as impressions on bedding planes below sudden blanketing influxes of sandstone or volcanic ash. This delicate mode of preservation makes the fossils relatively rare, but they are known from approximately 30 sites around the world.

Figures 1 & 2. Ediacaran fossils from Mistaken Point, Newfoundland

Ediacaran fossils range from centimetre-scale blobs to complex segmented discs and fronds over 1m long. Some were jellylike, while others had a more robust rigid structure that could be preserved in detail as fossils. None had actual hard skeletal parts such as shells or bones. The fossil assemblages became more diverse, and include more complex forms, with time. A wide range of shape and symmetry suggests the fauna was made up of distinct groups of organisms. It appears that all forms were benthic and occupied three feeding levels: an elevated level within the water column occupied by fronds; the seafloor level occupied by the discs; and a bottom level within the sediment occupied by burrowing wormlike forms.

The Ediacaran fauna includes the first definite fossil animals, some of which probably were the ancestors of later forms of animal life. Other Ediacaran forms are unknown in later life and were probably evolutionary experiments that died out. Prior to the Ediacaran fauna, life consisted largely of microbial communities, such as algal-type stromatolites. The oldest known Ediacaran fossils occur in the Mackenzie Mountains of northwestern Canada, in rocks that are approximately 600 million years old. The fauna persisted until just before the 'explosion' of life at the begining of the Cambrian Period. Their disappearance is probably due to competition and predation by the rapidly evolving Cambrian skeletal animals. The one possible exception is the fossil assemblage preserved in the Upper Cambrian rocks at Booley Bay, Co. Wexford, which has been assigned to the Ediacaran fauna. This apparently anomalously young age has led to doubts that the Booley Bay fossils are true Ediacaran types.

4 ORDOVICIAN - IAPETUS OCEAN AND VOLCANIC ARCS

The Iapetus Ocean began to close in the earliest Ordovician, and became progressively narrower throughout the period (Fig. 4.1). Traces of the former existence of Iapetus extend along the eastern seaboard of North America, through eastern Greenland, Ireland and Britain and into Scandinavia.

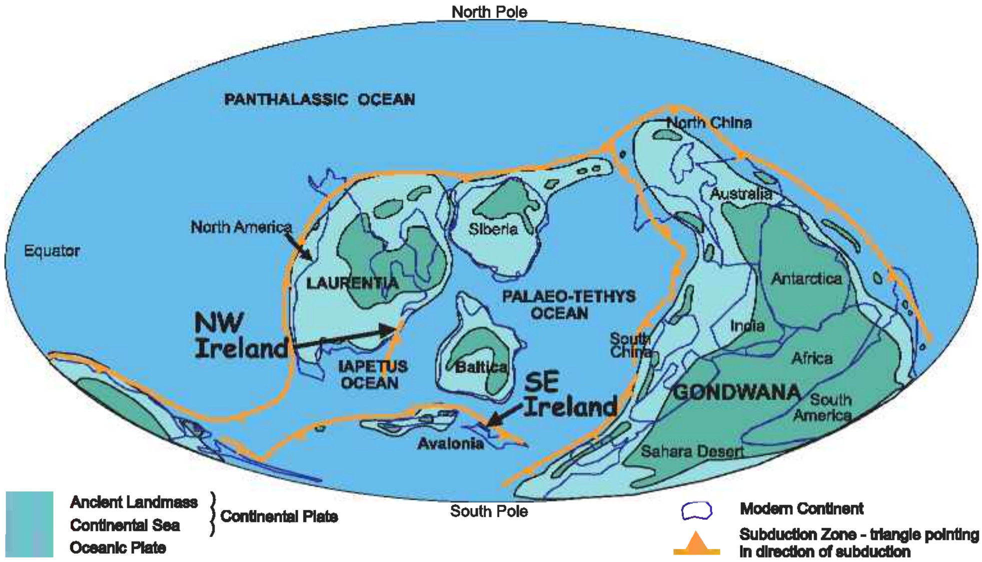

Figure 4.1 *Plate reconstruction for the middle Ordovician*

Fossil, palaeomagnetic, and other evidence indicate that the axis of Iapetus ran through central Ireland, roughly from the present day Shannon Estuary to Co. Louth (Fig. 4.2). Present day northwest and southeast Ireland lay along the margins of separate continental masses, with the Iapetus Ocean several thousand kilometres wide in between. Palaeomagnetic studies indicate that northwestern Ireland lay on the southern margin of the ancestral North American continent, Laurentia, just south of the equator. Southeastern Ireland lay on the micro-continent of Avalonia in the southern ocean, around 50° south. Shelly fossils from Ordovician rocks deposited on the separate parts of Ireland form distinct communities, indicating that the ocean was wide enough to form a barrier to migration.

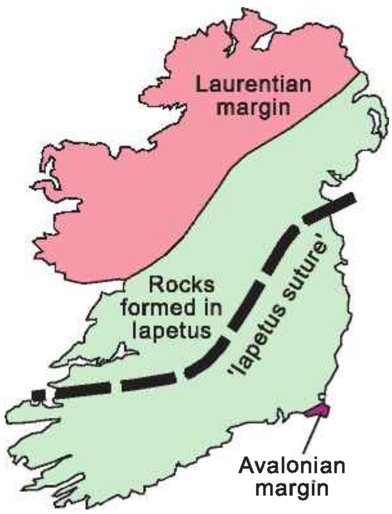

Figure 4.2 *Position of the Iapetus suture in Ireland*

4.1 SUBDUCTION OF IAPETUS & VOLCANIC ARCS

The Iapetus Ocean gradually closed, by subduction of the ocean floor (Study Box 4.1). As this happened volcanic rocks were erupted and intruded into the marine sedimentary sequences and the older crustal rocks, building up volcanic arcs along the margins and within the ocean. Ordovician rocks, 495 - 440 million years old, record a history of oceanic sedimentation and volcanic arc magmatism (Fig. 4.3), represented by a range of rock types including greywackes, mudstones, lavas and tuffs. Thick successions of Ordovician rocks from the Laurentian margin of Iapetus are preserved in South Mayo (see below), and from the Avalonian margin, in Wicklow to Waterford (see below).

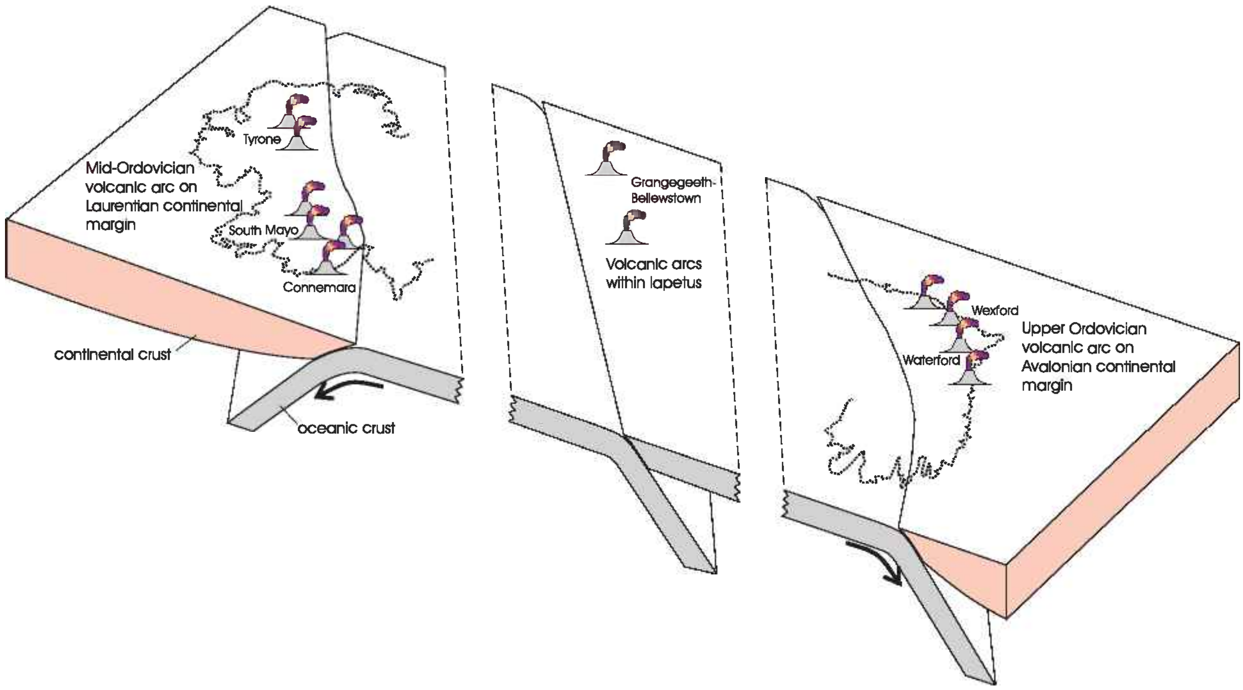

Figure 4.3 *Middle to late Ordovician volcanic arcs in the Irish sector of Iapetus*

Volcanic arc rocks, both lavas and explosively erupted tuffs, also occur in a belt between Navan and Collon (Counties Meath and Louth; known as the Grangegeeth volcanics). Shelly fossils from interbedded sedimentary rocks at Grangegeeth form a distinct community from those of the Laurentian or Avalonian margins of the ocean, indicating that they were deposited within the ocean, which was wide and a barrier to faunal migration. They were later sandwiched between the ocean margin sequences when the ocean closed in the Silurian.

As Iapetus closed during the Ordovician, the volcanic arc around its northern margin collided with Laurentia, causing a phase of deformation and metamorphism known as the Grampian Orogeny. In Connemara, large volumes of plutonic rocks of gabbroic to granitic compositions represent the deep intrusive level of a magmatic arc within the Laurentian continental margin. These rocks were intruded during the Grampian event and so were metamorphosed and deformed during intrusion.

As northward subduction of the oceanic plate continued, the late Ordovician and early Silurian sediments deposited on the ocean floor were scraped off against the northern continental margin as a series of fault-bound slivers. The wide band of Ordovician to Silurian sandstone and shale running from Down, through Monaghan and Cavan, to Longford (the Longford – Down Inlier, see below) was formed in this way. Volcanism along the southern margin appears to have ceased by the end of the Ordovician, suggesting that subduction had stopped. Subduction continued under the northern margin into the Silurian Period (see Chapter 5), though preserved volcanic rocks are sparse.

4.2 SOUTH MAYO

Ordovician rocks in South Mayo include lavas, tuffs, greywackes and mudstones that accumulated in a small oceanic marginal basin known as the South Mayo Trough. This trough developed during early Ordovician times, between an offshore chain of volcanic islands (island arc), formed as Iapetus gradually closed by subduction, and the Laurentian continent. A small area of related Ordovician rocks shows through the cover of younger rocks at Charlestown.

The earliest rocks to accumulate in the South Mayo Trough were volcanic rocks erupted from volcanoes on the southern side of the basin. They are well exposed in the area around Lough Nafooey. A major component of the Lough Nafooey locality is basalt pillow lava (Fig. 4.4), stacks of interlocking lava balls that formed when blobs of lava were chilled by eruption into water. Other volcanic rocks, such as tuffs and breccias are also present, as well as red and green coloured chert and black mudstones, the latter containing graptolites that indicate an early Ordovician age.

Figure 4.4 *Pillow lava from Lough Nafooey, Co. Galway*

Nearby volcanic rocks around Tourmakeady on the western side of Lough Mask are of andesitic to rhyolitic composition (Table 1.1). They occur mainly as coarse breccias and as lava domes of pale-coloured rhyolite studded with quartz crystals. These were also erupted under the sea, but the domes reached near the surface and small colonies of animals including brachiopods and trilobites lived on top of them, leaving patches of fossiliferous limestone. The fossils indicate that these rocks are younger than those at Lough Nafooey.

A great thickness of interlayered sand and mud accumulated on the floor of the South Mayo Trough over a period of 15 - 20 million years during the Ordovician. Volcanic ash deposits, generally called tuffs, occur throughout the Ordovician succession. They include ignimbrites, which are the deposits of explosively erupted flows of hot volcanic ash and gas. The lower part of the South Mayo Trough sequence comprises a 5,000 m thickness of greenish-grey greywackes and mudstones, deposited in deep-water by turbidity currents. The rather monotonous alternation of sandy greywacke beds and thinner interlayered slates, imparts a markedly ribbed texture to the landscape, well displayed in the Sheeffry Hills range. Local accumulations of coarse conglomerates within these rocks were deposited at the mouth of a submarine canyon, which cut across the southern margin of the South Mayo Trough. Shallow-water fluvial (Study Box 7.1) and deltaic (Study Box 10.1) conditions followed in which coarse, pebbly cross-bedded sandstones and conglomerates (Fig. 4.5) were deposited. However, basin subsidence kept pace with filling, so that the sandstones and conglomerates, exposed in the mountain range stretching from Mweelrea in the west to Maumtrasna in the east, are over 2,000m thick.

Figure 4.5 *Coarse conglomerate deposited by an Ordovician river, Co. Mayo*

4.3 WICKLOW – WATERFORD

The oldest Ordovician rocks on the Avalonian side of Iapetus, in Counties Wicklow, Wexford and Waterford, are fine-grained sedimentary rocks deposited as muds and silts in deep-water. These may in part form a continuation of the Cambrian sedimentation, but they represent finer sediment and indicate that the sedimentary basin became deeper and more distant from the sediment source. The deepening of the basin may have been a result of large-scale tectonic movements as Iapetus began to close by subduction. Subduction resulted in volcanic activity, which is recorded by local occurrences of basalts and andesites within the early Ordovician sediments, including pillow lavas. Volcanic activity is also recorded by deposits formed by the exhalation of metalliferous brines onto the sea-floor, subsequently metamorphosed to manganese-rich sedimentary rocks called coticule (Fig. 4.6).

Figure 4.6 *Folded coticule bands, Co. Wicklow*

Following deposition of the early Ordovician fine-grained sedimentary rocks and volcanics, there was a period of uplift and erosion caused by a minor orogenic event, mainly affecting rocks further to the south. Deposition of upper Ordovician rocks across the eroded lower Ordovician rocks therefore produced an unconformity (Fig. 1.34). This contact is exposed on the coast at Courtown in Wexford and at Tramore in Waterford.

The belt of Ordovician volcanic rocks shown on the map between Wicklow and the south Waterford coast, which includes interbedded fine-grained marine sedimentary rocks, are late Ordovician products of continuing subduction of Iapetus. They represent a mature volcanic arc, in which many of the magmas were of rhyolitic composition, which erupted explosively to deposit tuffs and volcanic breccias over a wide area. Local accumulations of basaltic composition were also deposited, notably around Bunmahon in Waterford. The volcanic arc apparently did not build up above sea-level and all its preserved erupted products were deposited under water, interbedded with fine-grained sedimentary rocks like those of the early Ordovician.

Rhyolitic volcanic rocks at Avoca, Co. Wicklow contain ore bodies of copper, lead, zinc and gold, deposited at the seafloor and within the rock by hydrothermal fluids during the period of volcanic activity. A long history of mining at Avoca ceased in 1983, after a total output of 16 million tons of copper ore. A small gold resource remains in place and exploration for further base metal resources continues.

4.4 KILDARE & DUBLIN

Volcanic activity of the same age as the Wicklow - Waterford belt is preserved in the Kildare Inlier, but here the volcanic rocks are predominantly andesite lavas. Their composition suggests they were erupted on the oceanward side of the volcanic arc. Similar lavas and intrusions, interbedded with tuffs and sedimentary rocks, are well exposed along the shore at Portrane and Balbriggan, in north Co. Dublin. Palaeomagnetic studies indicate that the Portrane - Balbriggan volcanic arc formed at around 50° S., on the southern margin of the ocean.

4.5 LONGFORD – DOWN

The Longford – Down Inlier comprises predominantly sedimentary rocks that are subdivided into two belts on the map; the Northern Belt is composed entirely of Ordovician rocks, while the Central - Southern Belt includes late Ordovician to Silurian rocks. The belts themselves are subdivided into northeast – southwest oriented fault bounded units of considerable lateral continuity that are stacked one on top of another. The stack was formed as slivers of sedimentary sequences were detached from the subducting Iapetus oceanic plate and added to the bottom of the stack at the edge of the Laurentian continent, to build a wedge called an 'accretionary prism' (Figure 4.7).

Accretionary prisms are a feature of plate margins at several subduction zones around the world today, for example, along the northwestern Pacific, where the Pacific plate is subducting under Japan. The rocks in an accretionary prism get progressively younger as later additions are made. Hence, the occurrence of entirely Ordovician rocks in the Northern Belt, and appearance of progressively younger Silurian rocks to the south in the Central - Southern Belt indicates that material was added to the southern side in this case, with subduction towards the north

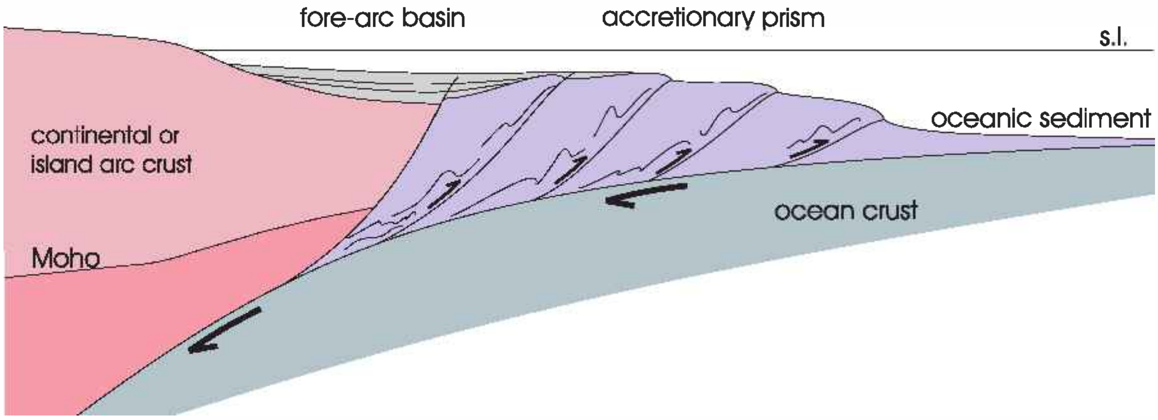

Figure 4.7 *Diagramatic accretionary prism, formed as sediments are scraped off the subducting ocean crust against the edge of the continent*

The Northern Belt comprises oceanic fine-grained sedimentary rocks and basaltic volcanic rocks that represent accreted fragments of Iapetus ocean floor. Each fault-bound sliver in the Central - Southern Belt is composed of a lower black shale unit, deposited in a deep ocean setting, overlain by greywacke sandstone deposited by turbidites coming off the continental margin. The change from black shale to greywacke occurs progressively later in the more southerly slivers, recording the progressive encroachment of continent-derived sediments onto the ocean floor as the Iapetus ocean crust was carried towards the continent during subduction.

4.6 ORDOVICIAN LIFE

A major diversification of a large number of groups took place during the Ordovician Period, particularly amongst shallow marine faunas with calcareous parts (Fig. 1.31). Rugose and tabulate corals and bryozoans achieved worldwide distribution by the end of the Ordovician, suggesting that clear warm shelf seas were widespread. Brachiopods (lampshells) also took advantage of this great range of shelf sea environments. The graptolites, which first appeared as bottom-dwelling forms in mid-Cambrian times, evolved planktonic types in the early Ordovician. These extinct colonial, branch-like animals with an internal tube connecting individual zooids along the branches, radiated and changed form so rapidly that the Ordovician and Silurian Periods can be divided into about 40 faunal zones using the fossils, which are correlatable worldwide. These fossils are so named because they are usually preserved as flattened carbonised films on bedding planes, resembling graphite pencil marks. The Ordovician also saw the development in the nautilus-type cephalopods (which originated during the Cambrian) of gas-filled chambers, each group showing various modifications designed to combat buoyancy problems. The simplest type of fish, the Agnatha, which lack jaws and paired fins and include heavily armoured forms, are first known in the Ordovician.

Study Box 4.1 - Subduction and volcanism at convergent margins

At convergent plate margins, two of the lithospheric plates that make up Earth's outer shell move towards each other. Where the plates meet, an oceanic plate is pushed down into the interior of the earth under the edge of the other, either oceanic or continental, plate in a process called subduction (Figure 1). Continental plates can't be subducted, because the rocks have relatively low density, so where two continental plates collide a huge crumple zone pushes up mountains.

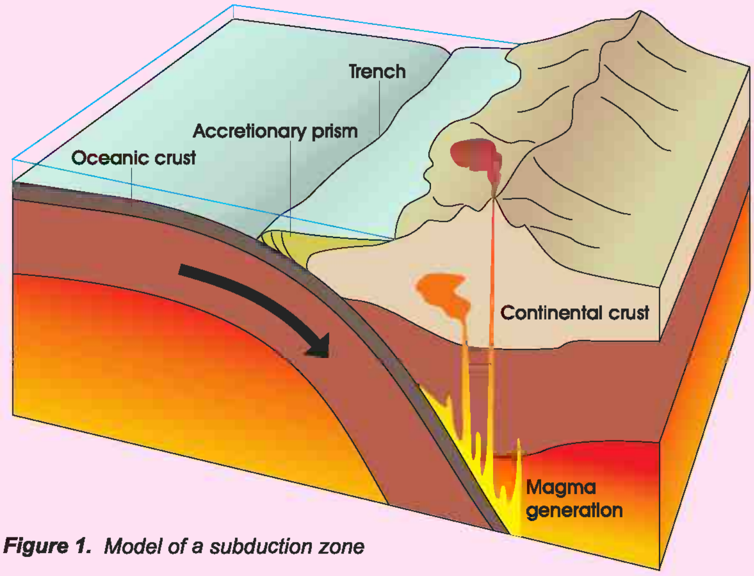

Figure 1. *Model of a subduction zone*

As the cold plate descends into the hot mantle, water is driven off it. This water lowers the melting point of the mantle, which partially melts to produce basaltic magma. The magma rises to form a chain of volcanoes along the edge of the overriding plate, called a volcanic arc. The Pacific "ring of fire" is a continuous line of active volcanic arcs formed as oceanic plates of the Pacific floor are being subducted under the Eurasian, North American and South American plates.

As it rises through the crust, the basaltic magma generated by partial melting of the mantle may change composition through crystallization or assimilation of crustal rocks. The magma will evolve to andesitic and perhaps to rhyolitic compositions, and as it does so its viscosity will increase. Increasing viscosity can have dramatic effects on how the magma erupts when it reaches the surface.

Figure 2. *Rangitoto, New Zealand*

Basaltic magma, having relatively low viscosity, tends to erupt gently and the lava flows away easily, so that basaltic volcanoes are commonly low and shield-shaped, for example the large, composite volcano of Hawaii, or the much smaller Rangitoto volcano of New Zealand, pictured here.

Andesitic magma tends to get stuck on the way out, until pressure from exolving gases builds up and the magma gets forced out explosively, scattering rock fragments and volcanic ash over a wide area. Alternations of lava and ash eruptions build conical mountains around the vent, producing the classical volcano shape, for example Taranaki in New Zealand or the Cascade volcanoes of western N. America.

The stickiest kind of magma is called rhyolite, and rhyolitic eruptions can be extremely violent. Rhyolite volcanoes are often depressions, called calderas, rather than mountains. Examples include Lake Taupo in New Zealand and Yellowstone in the USA.

Figure 3. *Taranaki, New Zealand*

SILURIAN - SEDIMENTATION IN THE CLOSING IAPETUS OCEAN

Continuous sedimentation from the Ordovician into the Silurian is seen in the rocks of the Longford - Down inlier, as mentioned in Chapter 4. These sediments were deposited by turbidity currents (Study Box 5.1) in the closing Iapetus basin (Fig. 5.1) and were then scraped from the northwards-subducting ocean plate onto the continental margin.

Elsewhere in Ireland, Silurian rocks are either in faulted contact with, or unconformably overlie, Ordovician and older rocks. As the Iapetus Ocean narrowed and the opposing continents were brought close to each other, the deep-water environment typical of the Ordovician was lost and several smaller, distinct sedimentary basins were formed. Some remained as deep-water, others were shallow and some were subaerial river basins rather than sea. As a consequence, the Silurian sedimentary rocks of Ireland comprise many different sequences deposited in different environments.

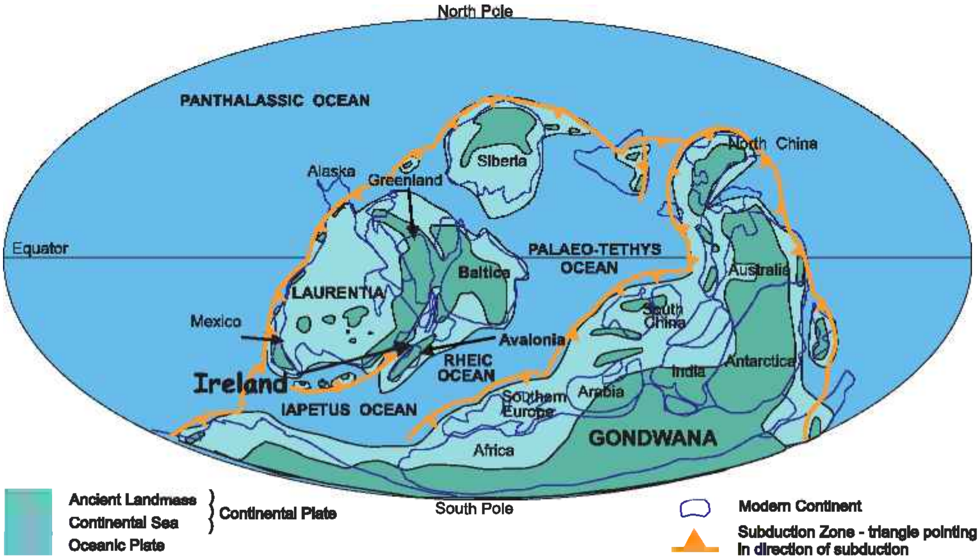

Figure. 5.1 *Plate reconstruction for the Silurian*

5.1 CENTRAL AND S.E. IRELAND

Deep-water sedimentation by turbidity currents continued in what is now central and southeastern Ireland. These rocks are rather poorly exposed in, for example, the uplands of the south midlands (e.g. Slieve Bloom to the Galtee Mountains) and in east Kildare. In general these Silurian sequences show a gradual upward transition to coarser grain-size, from mudstone and siltstone to greywacke, as the basins gradually became shallower and the continents that were the source of the sediments moved closer together.

5.2 DINGLE

The Silurian rocks of the Dingle Peninsula are very different from those in the midlands. By Silurian times the Dingle area was a coastal region in the southern tropics, and sediments were deposited in a shallow sea or on land by rivers. Many of the marine mudstones and sandstones are rich in fossils of the shellfish and corals that lived in the shallow sea. Dingle also includes the best record of Silurian volcanism in Ireland. Basalt lavas and rhyolitic tuffs around Clogher Head were erupted from volcanoes on land into the coastal environment, so that the volcanic rocks are interbedded with the shallow marine to non-marine sedimentary rocks. The relationship of the volcanism to the earlier subduction-related volcanism of the Ordovician is unclear, but it was probably due to late adjustments on the subduction zone as Iapetus finally closed and the continents were brought together.

5.3 NORTH GALWAY

Silurian sedimentary rocks between Killary Harbour and Lough Mask in northern County Galway lie unconformably on top of Precambrian and Ordovician rocks that were folded and faulted before the Silurian rocks were deposited. This sedimentary sequence shows an upward transition from alluvial sandstones, through beach and shallow marine sandstones with fossils, to relatively deep marine turbidites. The sedimentary basin, therefore, started as land and became progressively submerged by the sea, contrary to the trend of progressive shallowing seen elsewhere. The turbidites contain a lot of fresh volcanic grains, indicating that volcanoes were erupting nearby, although their location is not known and they are unlikely to be the volcanoes seen in Dingle. The upper part of the sedimentary succession shows a progressive return to shallow water conditions, with lagoonal mudstones at the top.

5.4 CLEW BAY

Silurian sedimentary rocks on the south side of Clew Bay include two distinct successions deposited in different environments. One succession, around Louisburg and on Clare Island, is composed of mudstones, siltstones and sandstones that contain ripple marks and desiccation cracks, and was deposited in an ephemeral playa lake in a semi-arid, non-marine environment. The adjacent succession to the east, including the rocks of Croagh Patrick, is formed of sandstones deposited in a shallow marine environment. These two successions are separated by a large fault and their original relative positions are not known.

Figure 5.2 *Bedded turbidites, Lough Fee, Co. Galway*

Figure 5.3 *Brachiopod fossils in Silurian marine sandstone, Co. Galway*

5.5 SILURIAN LIFE

The Silurian generally shows a continuation of Ordovician shallow marine invertebrate fossil types. A greater development of reefs was related to Palaeozoic seas reaching their maximum extent during this period. On land, early vascular plants (with connective tissues and woody cells enabling tall growth), such as ferns, evolved. Their emergence paved the way for the later evolution of land animals, such as the gastropods and insects, which would be interdependent on plant life. By the close of the Silurian, fish with primitive jaws, paired limbs and lungs (Placoderms) had appeared, their development forming an important evolutionary link to the emergence on land of the tetrapods during the Devonian. Fishes and plants had also colonised the fresh-water environment.

Study Box 5.1 - Turbidites and turbidity currents

Turbidity currents are flows of water laden with sediment that travel downslope under gravity in subaqueous settings. They are the main process by which sediment is transported into deep water in the oceans. Turbidity currents form by slumping of unstable sediment in relatively shallow water, which is commonly triggered by earthquakes. The disturbed sediment and water mixture then flows downslope, with the sediment kept in suspension by fluid turbulence, until the current slows down and the sediment is re-deposited. The flows are often channelled into deep water through submarine canyons at the edge of the continental shelf and, on emerging from the canyon mouth, build a submarine fan of sediment on the ocean floor similar to an alluvial fan.

Turbidity currents have not been directly observed in deep marine settings, but their occurrence has been noted by the breaking of submarine telegraph cables by passing flows. A well-known example is of a turbidity current that was generated by an earthquake on the Grand Banks, off the coast of Newfoundland, in 1929. The earthquake caused a huge volume of sediment to slump and flow downslope into the Atlantic for hundreds of kilometres at a maximum velocity of 70km h^{-1}.

The rocks deposited by turbidity currents are called turbidites. These form laterally extensive beds, typically a few centimetres to a metre or two thick, that build up into sequences many hundreds or thousands of metres thick in ocean basins. Since turbidity current events occur on a timescale of hundreds or thousands of years, thick sequences of turbidites in the geological record represent a huge amount of time. Much of Ireland's Ordovician and Silurian sedimentary rock sequence is composed of turbidites.

A typical turbidite bed has a distinctive internal structure, formed at different stages of the passage of the flow (Figure 1). The lower part contains the coarsest sediment, and this commonly shows grading; that is, coarsest at the bottom and becoming finer upwards, as progressively finer sediment settles out from the flow. Above this the sediment may show fine lamination, including ripples, produced as the weaker part of the flow passes over and adds to the deposit. The bed is capped by a layer of fine mud, deposited slowly from suspension after the flow has passed.

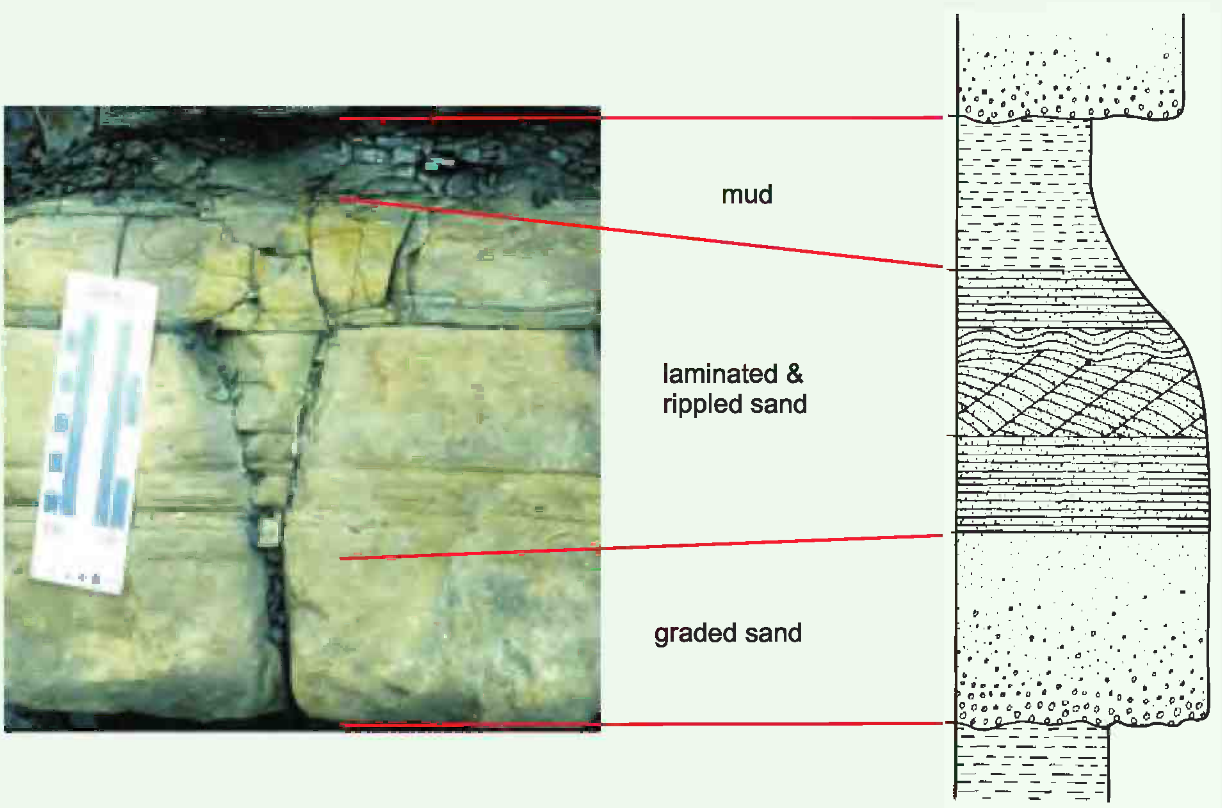

***Figure 1.** The internal structure of a typical turbidite bed*

6 CALEDONIAN OROGENY -MOUNTAIN BUILDING AND GRANITE INTRUSION

6.1 OROGENY

Throughout most of the Ordovician and Silurian Periods, the opposing continental margins of Iapetus had been creeping slowly towards each other due to consumption of Iapetus oceanic crust by subduction beneath them. Collisions of island arcs against the continental margins occurred during the Ordovician (for example causing the Grampian orogenic phase discussed in Chapter 4), but the point at which the opposing continental masses finally collided is still a matter of debate. Subduction of oceanic crust had largely ceased by the end of the Ordovician, but final closure, resulting in strong deformation of the rocks caught up between the two colliding continents, took place during late Silurian to early Devonian times. This later phase of collision and deformation is called the Acadian orogenic phase, and together the collisions and deformations resulting from the closing Iapetus Ocean are known as the Caledonian Orogeny. By the beginning of the Devonian Period, the land area of Ireland had been amalgamated on the southern, equatorial margin of the continent, Laurussia (formed from Laurentia, Avalonia and Baltica (Fig. 6.1)).

Just as the geologically recent and continuing collision of India with Eurasia has formed the Himalayas, so the combined effects of the Caledonian Orogeny raised a composite mountain chain from Ordovician to early Devonian times. Remnants of this ancient 'Appalachian - Caledonian' mountain belt are to be found today in Precambrian to Devonian rocks from the Appalachians of North America, through Ireland and Britain, to the Arctic Circle in Norway (Fig. 7.1).

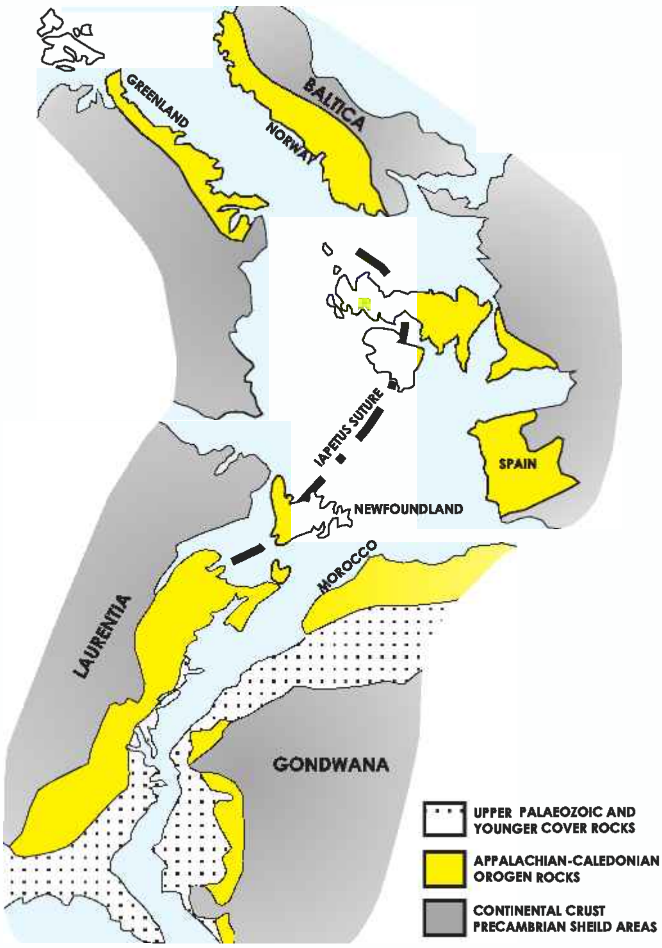

Figure 6.1 *The Caledonian Orogen*

The collisions were not 'head-on', but oblique, so that the continental margins slid past each other as they collided, with a left-lateral sense of movement, i.e. an eastward movement of the Avalonian microcontinent along the southern margin of Laurentia. This resulted in sideways displacement of slivers of the continental margins along major fault zones, as in the case of the infamous San Andreas Fault today in western North America.

As the collision of continents progressed, the rocks were folded and crumpled and faults cut and displaced rock sequences. In the Precambrian rocks, the Grampian, and any earlier phases of deformation, were overprinted by the Acadian deformation, resulting in complex structures in the rocks. Early folds were refolded about a different axis (Fig. 6.2) and several phases of movement on faults sequentially displaced previously related rocks. Late Ordovician and Silurian rocks were affected by only the Acadian phase, so that their deformation is relatively simple.

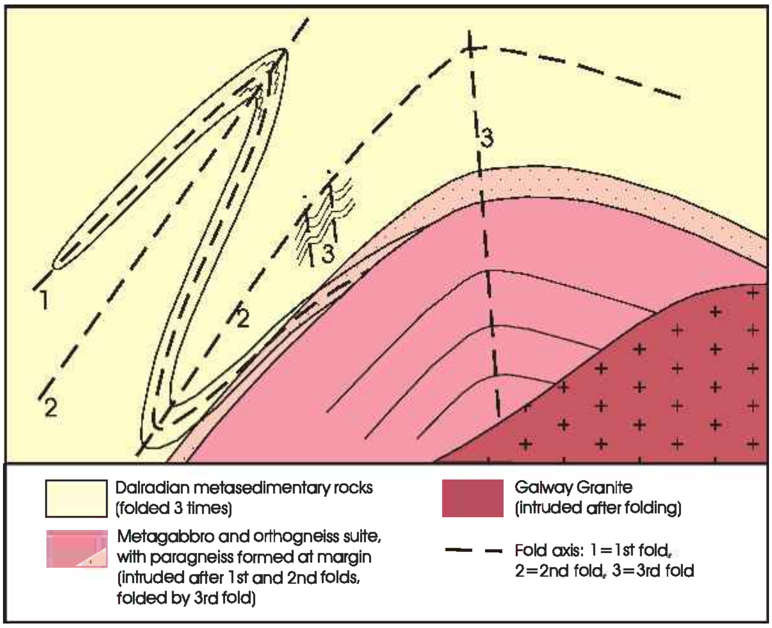

Figure 6.2 *Cartoon showing a sequence of folding of the Dalradian and intrusive igneous rocks of Connemara*

The effects of deformation can be seen on many scales: regional-scale folding of the quartzite in the Connemara Dalradian (Precambrian) rocks can be picked out on the map, while Fig. 2.2 shows small folds in an outcrop of Dalradian schist.

Although fault contacts are not distinguished on the map, many of the contacts between Precambrian, Cambrian, Ordovician and Silurian rock units are faults. For example, the contact between Ordovician and Ordovician - Silurian rocks running from north Down to Cavan on the map, is a major fault, called the Orlock Bridge Fault, that extends to the southwest across Ireland under the younger Carboniferous rocks and also extends to the northeast across Scotland.

The mountains of the Appalachian - Caledonian belt have long since been eroded away, mainly during the Devonian and early Carboniferous Periods, and the only vestiges we see now are the rocks that once lay deep down in the roots of those mountains, since lifted up to form much younger and smaller mountains. By the early Carboniferous, the mountains had been largely leveled by erosion, providing huge volumes of mud, sand, gravel and pebbles to build a new generation of rocks, the sedimentary rocks of the Devonian and Carboniferous Periods.

6.2 BASEMENT TERRANES

By the end of the Caledonian orogeny, the various crustal blocks that make up the geological basement of Ireland, which are composed of the Precambrian to early Silurian rocks discussed in Chapters 2 to 5, had been assembled in more or less their present arrangement. Distinct basement blocks with different geological histories that are subsequently juxtaposed by faults are called terranes. Figure 6.3 shows the terranes of Ireland and the intervening faults as they would be seen if the post-Caledonian rocks (i.e.younger than about 410Ma) were stripped off. Several terranes can be traced into the adjacent parts of the Caledonian orogen, to the east into Scotland and to the west into Newfoundland (Fig. 6.4).

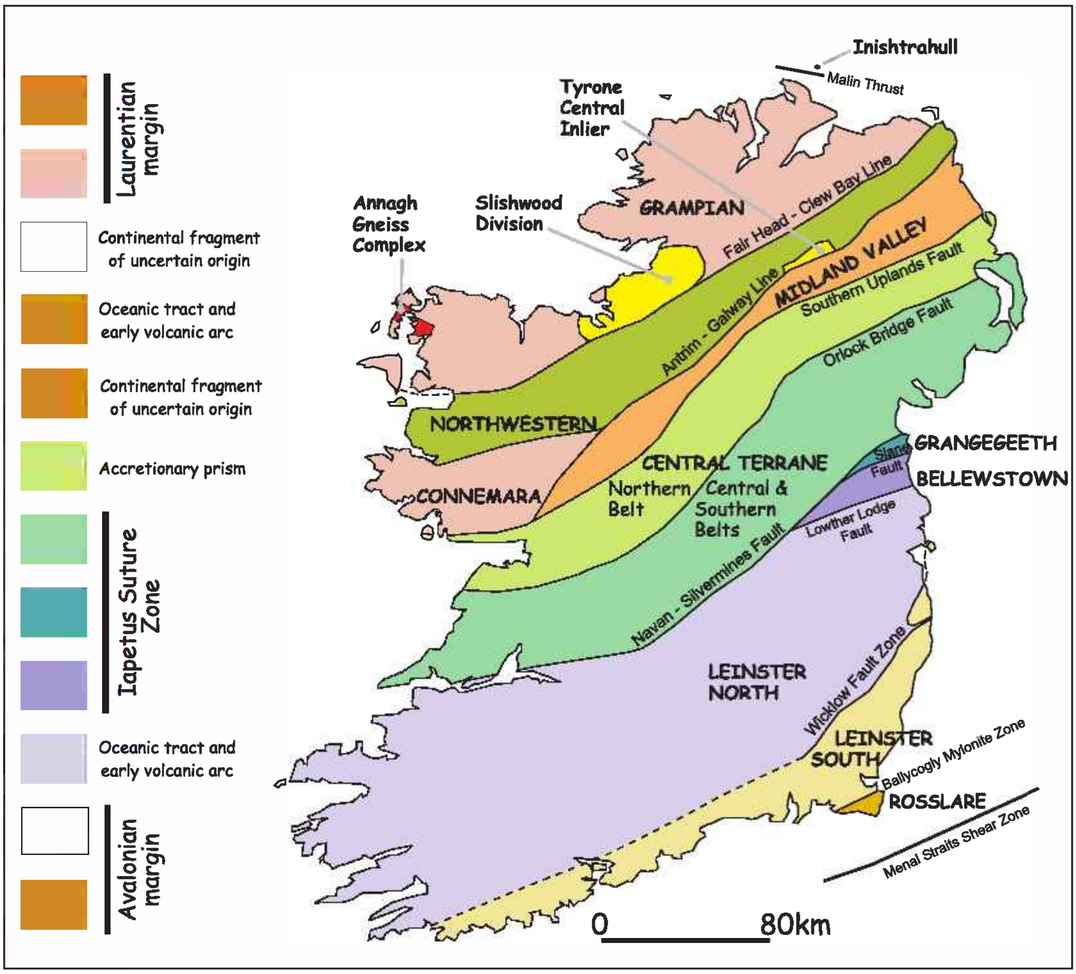

Figure 6.3 *Sketch map of the terranes of Ireland and the main terrane-bounding faults.*

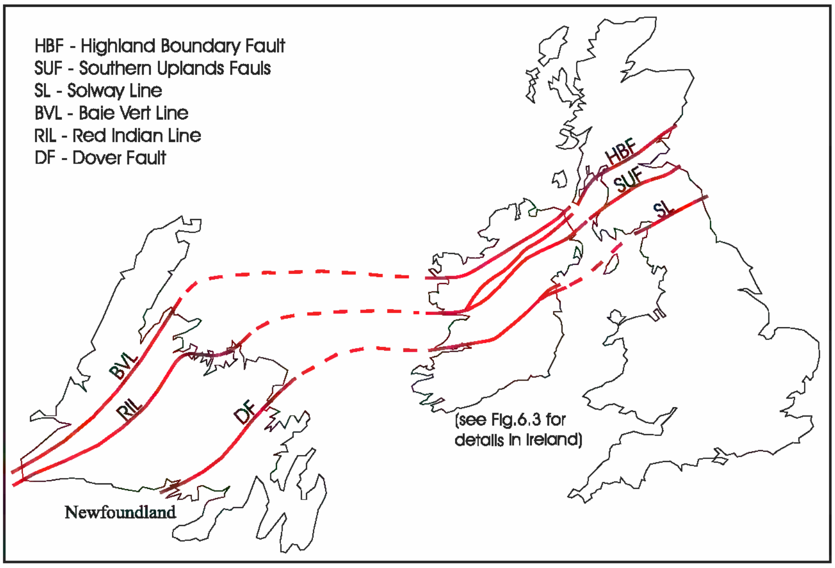

Figure 6.4 *Correlation of major terrane boundaries across the Newfoundland – Ireland – Britain part of the Caledonian orogen.*

6.3 GRANITES

Final closure of the Iapetus Ocean by continent-to-continent collision was accompanied by voluminous granite emplacement during late Silurian and early Devonian times (between 420 - 390 million years ago). This Caledonian magmatism was broadly contemporaneous with major sideways movements on faults and many of the granites were deformed as they cooled and crystallised.

Generation of granitic magma was from deep in the crust or at the crust/mantle interface. The granites were emplaced as molten rock that rose up large active faults in the crust, cooling and crystallising several kilometres below the land surface. Slow cooling allowed growth of crystals in the magma, producing coarse grained rocks (Fig. 6.5). The granites are now seen at the surface due to subsequent uplift and erosion.

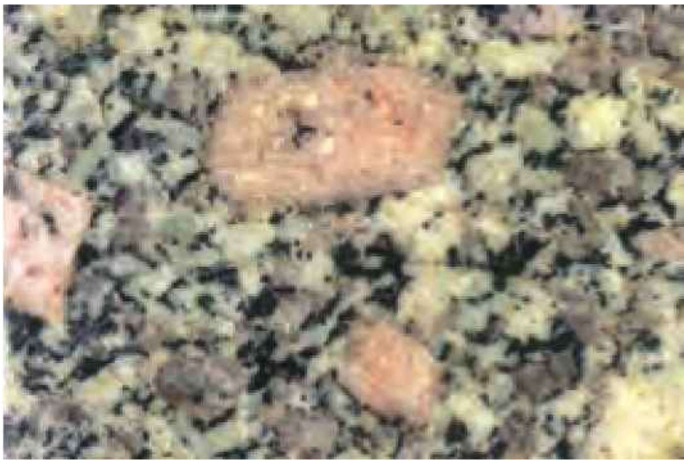

Figure 6.5 *Large pink feldspar crystals (up to 20mm across) in a matrix of pale coloured feldspars and quartz and dark coloured biotite and hornblende; Galway granite.*

A look at the map of Ireland will show that large granite bodies were intruded in Donegal, Mayo - Sligo, Galway, Carlow – Wicklow - Dublin and Armagh - Down (note that Armagh - Down also contains much younger Tertiary intrusions that will be dealt with separately in Chapter 14).

The several granite plutons that were intruded in Donegal, collectively known as the Donegal Batholith, have been studied in great detail and are known internationally as classic examples of granite intrusion. There are ten separate granite bodies in Donegal (Fig. 6.6), although some bodies are in contact with each other and many are composed of more than one pulse of intrusion. Although referred to simply as 'granite' they all range widely in composition and are complex bodies. Abundant minor granitic dykes accompany all the granites.

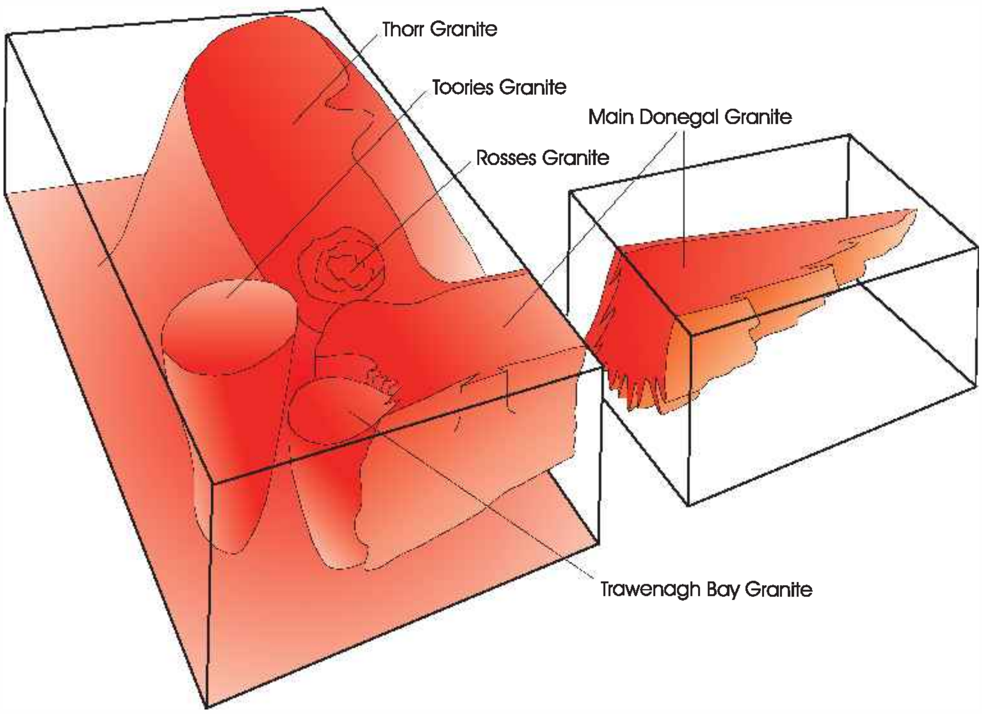

Figure 6.6 *Block diagram of the three-dimensional shape of part of the Donegal Batholith*

Three of the Donegal plutons, the Main Donegal Granite, the Barnesmore Granite and the Ardara Granite, are prime examples of three different mechanisms of granite intrusion.

Regional scale crustal shearing forces, between the Great Glen Fault to the north (offshore north of Ireland) and Highland Boundary Fault to the south, particularly affected the Main Donegal Granite during its intrusion and while it crystallised. Space for the granite was created by opposite sides of the northeast –southwest oriented shear zone pulling apart. The granite was intruded sequentially as a series of northeast -southwest trending sheets, more by accommodation than forceful intrusion, as more space was created. While shearing continued during and after intrusion, crystals in the granite were aligned and drawn out into a strong planar northeast – southwest fabric (Fig. 6.7). Slivers of Dalradian host rock were caught up between sheets of granite during intrusion and broken up to produce 'raft trains', elongate strings of blocks within the granite.

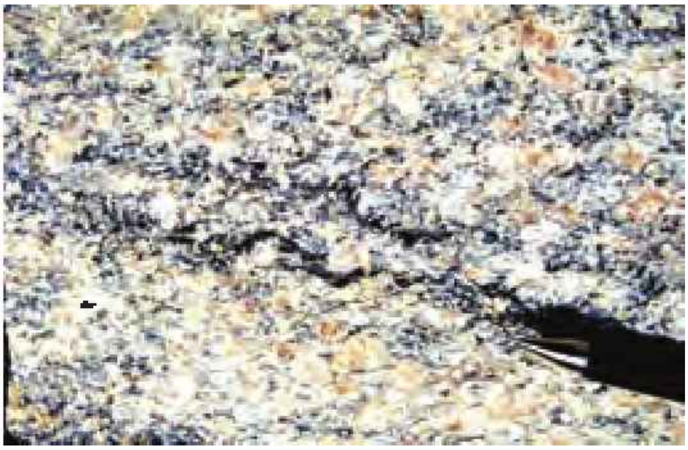

Figure 6.7 *Close up view of Main Donegal Granite, showing black biotite mica aligned by shearing during cooling of the granite magma*

The Barnesmore Granite, to the southeast of the main batholith, was intruded during cauldron subsidence. A large block of country rock detached itself along an upwardly convex dome-shaped fracture and subsided into underlying granite magma. The first pulse of granite was emplaced upwards into the space created. Further subsidence caused two more pulses of granite intrusion that sequentially cut the solidified earlier intrusions.

The Ardara Granite was intruded as a diapir, a turnip-shaped body of magma that rose through the crust under its own buoyancy, followed by radial expansion like a balloon to increase the pluton's overall size. The expansion of the granite caused concentric compression of the outer part of the granite and its host rock around its almost circular contact.

7 DEVONIAN - 'OLD RED SANDSTONE' RIVERS & DESERT

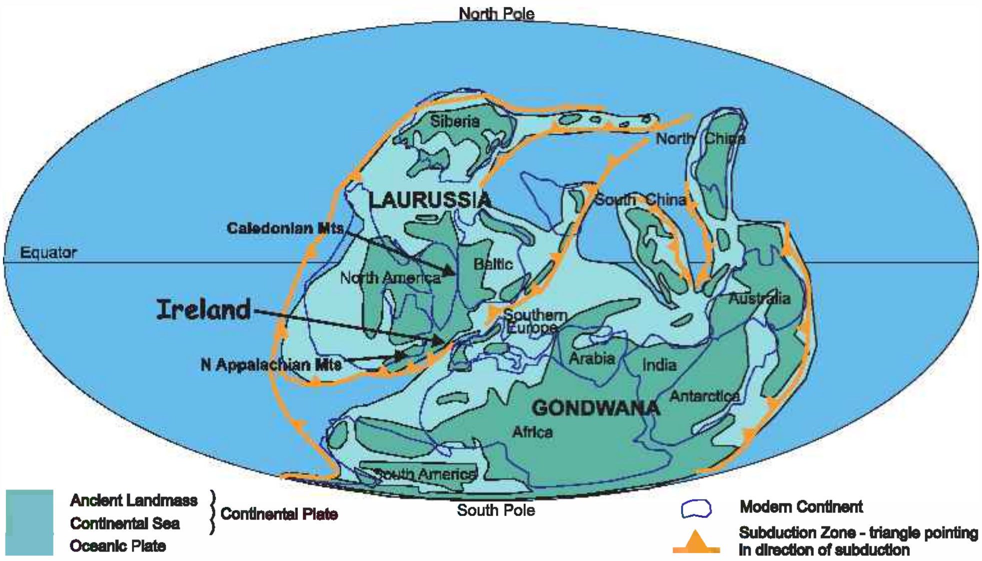

Figure 7.1 *Plate reconstruction for the Early Devonian (390 million years ago)*

7.1 CLIMATE & SETTING

During the Devonian Period, which lasted from 410 - 354 million years ago, Ireland was located on the southeastern margin of a large 'Old Red Sandstone' landmass that had formed from the final closure of the Iapetus Ocean during Silurian times (Fig. 7.1) (Chapters 5 & 6). This landmass on the Laurussian Plate covered most of what is now northern Europe and North America.

From the mid-Devonian onwards, Ireland, as part of the landmass, gradually moved from about 35^{O}S northwards towards the equator. The climate was semi-arid, with seasonal rainfall, Ireland being on the windward side of the continent, similar to the position of Zimbabwe today. Erosion of the Caledonian Mountains (Chapter 6) in northwest Ireland supplied sediment via large rivers to the extensive deserts of the alluvial plains.

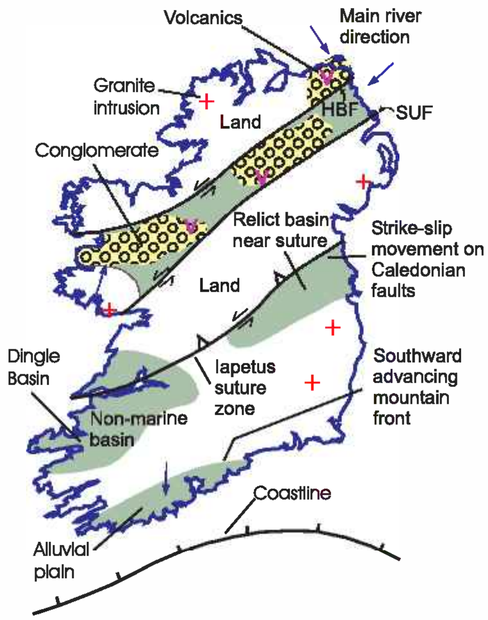

Figure 7.2 *Lower Devonian palaeogeography*

The predominantly red or purple colouration of the rocks, which gives rise to the name 'Old Red Sandstone' is due to the arid climatic conditions and low water table causing oxidation of the sediments (Study Box 7.2).

River processes dominated sedimentation in Ireland until the latest Devonian when the sea inundated most of Munster from the south. Evaporites and aeolian sediments were uncommon, compared to the later 'New Red Sandstone' deserts of the Permo-Trias (Chapter 11). Plants and trees flourished wherever the water table was high enough to prevent oxidation of the sediments. Bioturbation (Study Box 8.2) in mudstones from the Upper Devonian indicates that there was also an abundant fauna.

7.2 LOWER DEVONIAN BASINS

During the Lower Devonian, sedimentary basins (see section 1.4.2) were mostly restricted to the northern part of the country, exposed now near Clew Bay, the Curlew Mountains, Fintona, and Cushendall (Fig. 7.2). This was a mountainous area raised up in the last phase (Acadian) of the Caledonian Orogeny (Chapter 6, Fig. 6.1). The basins were internal basins (intermontane) within the mountain zone, that probably subsided between the Highland Boundary and Southern Uplands faults, which were active at this time (Figs 6.3, 6.4). These faults moved laterally by strike-slip displacement (see Fig. 1.35) as a result of the orogeny and extended into Ireland from the Midland Valley of Scotland, where there are similar Lower Devonian basins. They are characterised by conglomerates and sandstones and interbedded volcanic layers. Many of the conglomerate clasts are also derived from volcanic rocks. The conglomerates and sandstones were deposited in alluvial fans, playa lakes and associated fluvial deposits.

In the south of Ireland Lower Devonian rocks are preserved in another small basin on the Dingle Peninsula (Fig. 7.2). Here sedimentation was continuous from the Silurian into the Lower and Middle Devonian. The basin contains conglomerates and sandstones interpreted as lake sediments fringed by debris fans and later fluvial deposits.

At Inch, purple conglomerates contain clasts of metamorphic rocks that were probably derived from an area of now unexposed metamorphic rocks to the south (Fig. 7.3). This alluvial fan spread northwards down the southern slope of the Dingle Basin. Red sandstones and siltstones deposited between the conglomerate beds reveal sedimentary features, such as cross-bedding and ripple marks that are typical of an alluvial setting. Mud (desiccation) cracks formed on the surface of wet mud, indicate rapid drying-out of a playa lake in the hot desert environment.

Figure 7.3 *Conglomerates at Inch Strand, Co. Kerry*

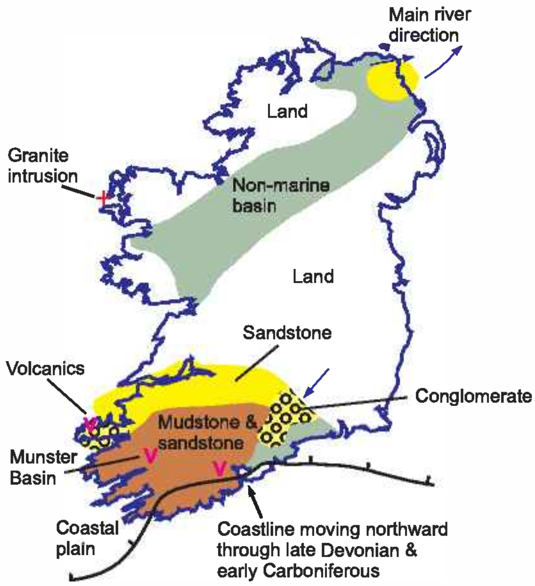

Figure 7.4 *Late Devonian palaeogeography*

7.3 MIDDLE & UPPER DEVONIAN

Most of the Devonian rocks preserved in Ireland today are of Upper Devonian age and rest unconformably on eroded Silurian rocks. Rocks of Middle Devonian age are generally absent, as this was a time of erosion marked by an unconformity (section 1.5.2; Fig. 1.34). However, rocks of Middle Devonian age have already been noted in the Dingle Basin. Rocks of late Middle Devonian age are also recorded from the Munster Basin.

7.3.1 THE MUNSTER BASIN

The Munster Basin (Fig. 7.4) was the site of the thickest non-marine Devonian sequence in Europe, with more than 6 km of sedimentary rocks deposited in the deepest part over the Iveragh Peninsula. It began in Middle Devonian times and continued throughout the Upper Devonian. The northern margin extended eastwards from Dingle Bay, through the Galtee and Comeragh mountains to the Waterford coast.

The basin is filled with conglomerates, sandstones, siltstones and mudstones. Two major river systems, that were eroding the mountainous source area to the north, dominated deposition in the Munster Basin. One entered the basin over the Iveragh Peninsula in the west and the other eastern river deposited its load over the Galtee Mountain region. Deposition from these rivers gave rise to the following four main packages of sedimentary rocks.

7.3.1.1 COARSE GRAINED FLUVIAL ROCKS – ALLUVIAL FANS & BRAIDED RIVERS

The coarse-grained conglomerates are found mostly on the margins of the basin, for example in the Comeragh and Galtee Mountains, where they represent alluvial fans (Study Box 7.1). These conglomerates can be seen in the back-wall of the corrie lake at Coumshingaun, Co. Waterford.

In the northern part of the basin, sedimentary structures in the pebbly sandstones and coarse sandstones show that the rivers were braided, that is, the channels split many times and joined up again as they flowed southwards across the alluvial plain (Study Box 7.1). The silt and mud sized material was carried away in suspension much further south.

7.3.1.2 AEOLIAN SANDSTONES

Sometimes, but not commonly, coarse alluvial fan deposits are interbedded with aeolian (wind-borne) sediments. This is seen on the northern margin of the Galtee Mountains, where fan conglomerates building outwards from the north interfingered with sands of an aeolian dune field (Study Box 7.2). Large-scale cross-bedding in the dunes (foresets of up to 15 m thickness) indicate that the main wind transportation was from the south. Similar juxtapositions of coarse alluvial deposits and aeolian sediments can be seen, for example, at Kilmurray Bay (Fig. 7.5) and Inch on the Dingle Peninsula.

Figure 7.5 *Aeolian Sandstones, Kilmurray Formation, Dingle.*

7.3.1.3 FINE-GRAINED FLUVIAL ROCKS – UNCONFINED SHEETFLOODS & LAKES

Further south, into the central part of the basin, the deposits are generally finer grained and result from unconfined sandy sheetfloods. In the hot, semi-arid climate, the mountains were periodically exposed to torrential rains, generating flash-floods in dry river valleys that caused rapid erosion. The rivers flowed mostly seasonally towards the south, ending in an extensive lacustrine area where the water seeped into the sediments. Drainage and evaporation far exceeded rainfall, and the lakes that formed on the plains, similar to those seen now in

South Australia, were short-lived. There were, however, a few perennial rivers. This finer grained predominantly purple coloured siltstone and mudstone (Fig. 7.6) makes up the great bulk of the Old Red Sandstone sequence, reaching several thousand metres in thickness along the peninsulas of West Cork and Kerry.

Figure 7.6 *Fine-grained floodplain deposits*

7.3.1.4 FLUVIAL COASTAL PLAIN SANDSTONES

Towards the top of the Old Red Sandstone succession, thick green and yellow sandstones appear and represent the transition from totally non-marine, well-oxygenated Old Red Sandstone fluviatile rocks, to the latest Devonian marine influx, marked by a higher water table and less oxygenated conditions. These sandstones were deposited by rivers on the coastal plain and can be seen at places such as Toe Head and Mizen Head in West Cork.

At around the same time micaceous white and yellow sandstones were being deposited in the eastern part of the basin, where they now crop out around the Galtee, Comeragh and Slievenamon Mountains. An interbedded green siltstone layer with beautifully preserved fossils of fish and plants (for example, *Archaeopteris* – Fig. 7.7) was discovered in the 19th century from a quarry at Kiltorcan, County Kilkenny. The siltstone was probably deposited by a highly sinuous river, on point bars and in adjacent swamps.

Figure 7.7 *Archaeopteris*

7.3.1.5 LATEST DEVONIAN MARINE SANDSTONES & SHALES

Tectonic rifting in latest Devonian times resulted in the formation of the smaller South Munster Basin, south of a line from Cork to Kenmare. In the uppermost Devonian, the sea encroached across this basin depositing dark-grey sandstone, siltstone and mudstone. Sedimentary structures show that there was wave and tidal current action (see Chapter 8; Study Box 8.1). The presence of brachiopod fossils also demonstrates their marine setting. This marked the beginning of a thick marine clastic sequence that continued uninterrupted in the South Munster Basin into Upper Carboniferous times. At the Old Head of Kinsale, these uppermost Devonian marine rocks are around 900 m thick and pass upward into dark-grey Carboniferous mudstones.

7.4 LATE DEVONIAN ROCKS IN THE MIDLANDS

On the map, rocks of Old Red Sandstone type surround the Silurian upland areas such as Slieve Bloom, Slieve Aughty and Slieve Phelim. These rocks comprise a widespread and relatively thin (generally less than 300 m) sequence of conglomerate, sandstone, siltstone and mudstone laid down to the north and east of the Munster Basin. The sandstones were mostly deposited from laterally migrating, low sinuosity rivers flowing southwards. Some of these rivers were of comparable size to the larger rivers in the British Isles today. Sandstone-mudstone interbeds are interpreted as deposits of vegetated floodplains beneath which the water table was rising. Conglomerates and pebbly sandstones, such as those found at Dunmore East (Fig.7.8) and Hook Head, were deposited in less sinuous, bedload dominated rivers closer to the higher ground of the Leinster Massif. This alluvial plain facies migrated slowly ahead of the northward advancing sea with uninterrupted fluvial deposition continuing upward into earliest Carboniferous times. In fact, most of the Old Red Sandstone in the north midlands is Lower Carboniferous in age.

Figure 7.8 *Old Red Sandstone conglomerate and sandstone at Dunmore East, Co. Waterford.*

7.5 DEVONIAN VOLCANOES & GRANITES

The presence of interbedded lava flows and ash fall deposits in the Old Red Sandstone, demonstrates that volcanic activity was contemporaneous with sedimentation. During the Lower Devonian in the Curlew Mountain area, thin andesitic lava flows (see Table 1.1) and pyroclastic layers alternated with sheetflood mudstone deposition on the downstream part of an alluvial fan.

Volcanic activity continued throughout the Middle and Upper Devonian in both northern and southern Ireland. The abundance of volcanic clasts and thin lava flows of this age (around 376 million years ago) in the Clogher Valley (Fintona) conglomerates, suggests that this alluvial fan was built up almost entirely from eroded contemporaneous volcanics.

Tuffs interbedded with the siltstones on the Iveragh Peninsula are dated at around late Middle Devonian (385 million years ago) and may be of similar age to the dolerites and gabbros intruded in the Valentia Island Harbour area. Southeast of Killarney, a similar-aged volcanic complex at Lough Guitane consists of mostly acid lavas and tuffs interbedded with alluvial fan channel sediments. Most of the volcanism and granite intrusion at this time appears to be related to the final stages of subduction of Iapetus oceanic crust. The rise of magmas was apparently controlled by strike-slip movement along major faults (see Chapter 6).

7.6 DEVONIAN LIFE

Major changes took place in the fauna and flora at the Silurian – Devonian boundary (Fig. 1.31). The changes were mostly in the terrestrial environment. Vascular plants continued to rapidly colonise the land, leading to dense forestation by the end of the Devonian, a time when seed-bearing plants (gymnosperms) also appeared. Heavily-armoured fish and primitive bony fish were abundant in the shallow fresh-water lakes of the Lower Old Red Sandstone, and sharks had evolved by mid-period. Later in the Devonian, 'tetrapod' amphibians (such as *Ichthyostega*) became the first animals to walk on land. Insects appeared in the early Devonian and the first winged type insect was reported from Upper Devonian rocks in Russia. Coral reefs and fish were abundant in the marine environments now recorded in southwest England and continental Europe. The goniatite group of ammonoids had evolved at the start of the Devonian and would become abundant in the Carboniferous seas that covered Ireland.

7.7 THE VALENTIA TETRAPOD TRACKWAY

Figure 7.9 *The tetrapod trackway on Valentia Island, Co. Kerry.*

A large number of fossil footprints (Fig. 7.9), forming several trackways, have been exposed on some of the bedding planes in the purple siltstones on Valentia Island. They were made by the first known tetrapod, a primitive amphibian that probably evolved from a type of lungfish, as it walked across the fluvial plain. From the two hundred or more footprints, complete with body and tail drag groove, it has been possible to calculate a body length of about one metre and to envisage a salamander-type gait. As the first discovery of this type in Europe and the oldest *in situ* record of an amphibian animal, the site is now protected as an important part of Ireland's heritage.

7.8 DATING THE ROCKS

Old Red Sandstone rocks are very difficult to date because of the paucity of fossils, due to the hostile conditions of deposition and preservation. They have been dated mainly on the basis of plant pollen (miospores), which evolved rapidly, but which are generally absent from all but the upper Old Red Sandstone. Radiometric dating of interbedded volcanic rocks have yielded absolute ages of late Middle to Upper Devonian (around 385 - 376 million years ago) for sedimentation in the Munster Basin.

STUDY BOX 7.1 - Alluvial Systems

A river is a dynamic system that constantly adjusts its flow (discharge), sediment transport and channel geometry in response to changes in slope and base level (Study Box 15.1). Debris that rivers carry as sediment is deposited as alluvium on the valley floor. When a mountain tributary stream moves from a steep gradient to a flatter gradient, where for example it joins the main valley, its velocity suddenly slows and its sediment load is dumped as an alluvial cone or alluvial fan. Coarser material, comprising boulders, cobbles and gravel, is deposited on the steeper upper slopes, while the finer sand, silt and mud are carried further onto the lower, gentle slopes.

Figure 1. *Alluvial fan, Andes, Argentina*

Fans from adjacent streams along the mountain front may coalesce into compound fans that can build up into a great thickness of sediment over millions of years. In a desert environment (Study Box 7.2), periodic torrential rainstorms produce flash floods which are highly erosive; the streams carry vast amounts of loose debris that add to the alluvial fans (Fig. 1). In the Mohave Desert, California, cone-shaped fans have built up at the foot of each narrow mountain valley, so that the lower slopes are totally covered.

Braided Streams - are typical of high-energy rivers (high load, low to variable slope and flow) flowing across the upper reaches of an alluvial valley plain.

The channel fill of braided streams is defined by a basal erosional surface, and cross- stratification from the downstream migration of bars. Fining-upwards of grain size is common (Figs. 2 & 3).

Figure 2. *Braided alluvial plain, Nazca, Peru*

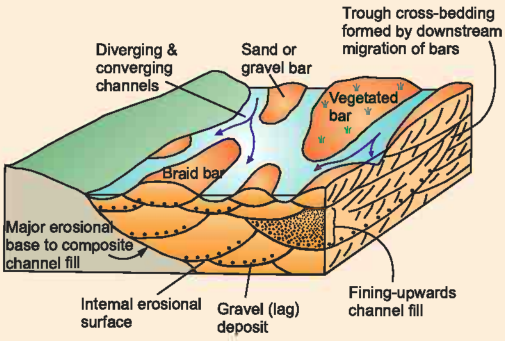

Figure 3. *Internal structure of a braided river*

Meandering Rivers - Low-energy rivers flowing across lowland plains carry a fine sediment load (sand, silt or mud) and develop a sinuous or meandering pattern. Some meandering rivers (Fig. 4) erode deeply into the bedrock during uplift (Study Box 15.1) and thereby become entrenched, for example, the Grand Canyon of the Colorado River.

The sideways movement of meanders is formed by erosion along the outside of the bend (where the current is strongest) and the deposition of a curved bar, known as a point bar (Fig. 4), on the inside of the bend (where the current is weakest). Some meanders on the Mississippi River migrate by as much as 20 m a year. As meanders migrate sideways and downstream, point bar and channel deposits of gravel, sand and silt accumulate across the valley floor, creating a wide flat floodplain.

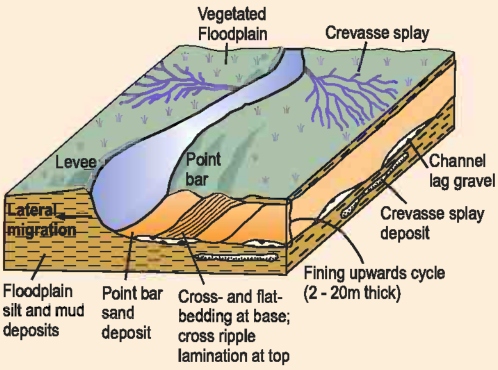

Figure 4. *Internal structure of a meandering river*

Point bars show cross-bedding in cross-section, and the downcurrent direction of these bedding patterns has been recognised in geological strata and used to determine flow directions of ancient river systems (palaeocurrent indicator).

If meander loops get too close together, the river may take a shortcut, leaving behind the abandoned bend as an oxbow lake. These fill with mud and silt and eventually support reeds and other vegetation. The floodplain also consists of finer grained overbank deposits of silts, clays and some sands, dumped across the floodplain in times of river flooding; such floodplain deposits are horizontally bedded and rippled. When a river breaches its banks, it suddenly drops its coarsest material along the sides, to form ridges that build up into confining levees after successive floods (see Study Box 10.1).

Study Box 7.2 Desert Processes - Erosion and Dunes

Desert areas form about one fifth of the world's land area and were as extensive, if not more so, in the geological past. Today, most of the great deserts lie in the tropics. The cold polar deserts, however, should not be forgotten. The main agents of erosion and deposition are water and wind (Fig. 1), with mechanical and chemical weathering helping to shape the desert landscape. However, rainfall is rare and sporadic, and temperature and wind power fluctuate dramatically on a daily and seasonal basis. The erosive and depositional power of water is described in Study Box 7.1.

Mechanical erosion predominates over chemical methods, involving splitting, exfoliation and disintegration of the rocks by the alternation of hot and cold extremes, forming steep scree slopes with angular rubble at the base and smaller rock fragments across the plains. Chemical weathering is extremely slow but plays an important role. Decomposition and solution weakens the rocks so that they are vulnerable to mechanical attack. Evaporation brings minute quantities of dissolved matter, including iron oxides (e.g. haematite), manganese and clay minerals, to the surface to form an oxidized red or brown film on rock and pebble surfaces, known as 'desert varnish'. It appears to take about 2000 years to 'varnish' a desert monument or artifact. Oxidation is a chemical weathering process where iron takes up oxygen, as when an iron bar goes rusty. Some of the rocks are green coloured and this reflects reduction, the opposite of oxidation, due to a high water table preventing air from reacting with the iron in the rocks.

Figure 1. Alternating hard & soft rock layers in Jurassic rocks, Goblin valley, Utah, when joints & bedding surfaces are eroded by wind & water, result in differential erosion & the formation of 'goblins'.

About one fifth of desert areas are covered by sand (Fig. 2). Much of the desert floor is bare bedrock strewn with coarse rock fragments, and only a sandy bedrock layer will yield sand on erosion. The sand grains are then whipped up by the wind, transported and shaped into a variety of mounds, ridges and dunes (Fig. 2). Form and pattern depend on many factors, including the grain size and type, the underlying rock surface and the strength and direction of the wind. Any obstacle to the wind, such as a rock or pebble, can be the starting point for dune formation. Sand accumulates downstream of the object, in the wind-shadow, which initially forms a sand drift. This may grow into a larger dune, given a constant sand supply and prevailing wind direction. Sand grains roll up the gentle windward slope and fall down the slip face, forming a foreset (in the same way as fluvially-formed cross-bedding Study Box 8.1) and thus advance the dune downwind (Fig. 3). Crescentic shaped dunes (barchans) occur as single units on bare bedrock where sand supply is limited, or as colonies that migrate across the desert like giant ripples. Consistent wind direction, as found in the Trade Winds areas, enables growth and stability in barchan colonies, as seen by their great procession through the Libyan Desert. Dunes often reach heights of 30 m and the mountainous dunes of the Saudi Arabian desert can reach 250 m. There is an inbuilt height limitation, as wind velocity increases higher up, thus removing sand from the top of the dune.

Figure 2. Sand Dunes in the Sahara, Mauretania

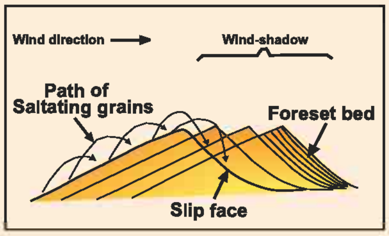

Figure 3. Sand dune formation

When the rock surface between irregularly spaced barchans and ridges is sprinkled with coarse sand and fragments, the wind disperses any loose sand into featureless sand sheets, rather than forming separate dunes. Sand sheets merge with other dune types to form an extensive dune field (or 'sand sea' or erg), often with smaller ripples developed on the dune surfaces, as seen in the Egyptian Desert.

Figure 4. Aeolian cross-bedding, in Jurassic sandstones, San Rafael Swell, Utah

In the geological record, large-scale cross-bedding is recognised as the product of ancient deserts, and gives direct evidence of palaeowind directions (Fig. 4).

8 EARLY CARBONIFEROUS – SANDSTONE AND SHALE

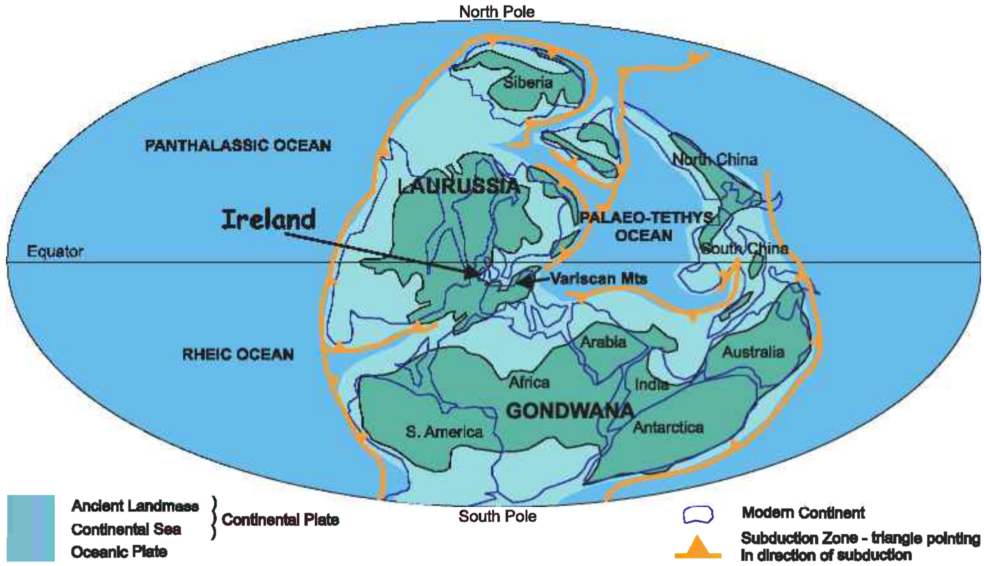

Figure 8.1 *Plate reconstruction at the beginning of the Carboniferous Period*

At the end of the Devonian, Ireland was in tropical latitudes, near the equator (Fig. 8.1) on a stable platform well away from any plate boundaries. The sea encroached on the southwest of Ireland depositing sand and mud eroded from the Old Red Sandstone continent. This transgression continued into the Carboniferous (which started 355 million years ago) covering most of Ireland south of Galway and south of the Leinster Massif (Fig. 8.2). The sea was shallow, shown by various sedimentary structures contained in the sandstones and shales. In the early Carboniferous, environments ranged from estuarine and shoreline beach deposits, to tidally influenced and sub-tidal wave-reworked and storm influenced shallow marine.

Figure 8.2 *Palaeogeography of the earliest Carboniferous times*

For the sea to encroach so far north in a short time it can be assumed that the land surface was low lying – a broad coastal plain. Some areas, however, were high ground, such as the granite area of the Leinster Massif (Wicklow and Blackstairs Mountains) intruded in the early Devonian. The presence of granitic granules in the early Carboniferous sandstones surrounding the Leinster Massif, in Co. Carlow, shows that the granite was being actively eroded at this time.

The march northwards of the various environments from beach, through tidally influenced, to sub-tidal environments of moderate water depth can be traced in the geological record. In a generalised way it can be seen on the palaeogeographical reconstruction (Fig. 8.2) where the shallowest deposits are to the north and pass southwards into deeper offshore deposits at the present south coast. Absolute water depth is very difficult to estimate, as many sedimentary structures such as cross-bedding and current ripples (Study Box 8.1) can be found in a number of different environments at different depths.

The evidence of early Carboniferous shallow-water environments is recorded mostly in sandstones and shales. Many of the rocks from the early Carboniferous are mixtures of sandstone and shale and even some thin limestones and are sometimes referred to as the 'Lower Limestone Shale'. The sandstone/mudstone mixtures are called *heterolithic* and comprise various proportions of sand and mud (Fig. 8.3). They often contain a number of sedimentary structures and trace fossils of burrowing or grazing animals which may have so stirred around the original sediment that the original bedding and sedimentary structures have been destroyed (Study Box 8.2).

Over much of the country these rocks may only form a sequence about 40 – 50 m thick. They are often very poorly exposed especially inland. One of the best places to see the transition from late Devonian fluvial Old Red Sandstone rocks through the early Carboniferous tidally influenced and shoreface sandstones and shales, into the Carboniferous Limestone, is at Hook Head, Co. Wexford, where the sequence is exposed in low cliffs along both sides of the peninsula.

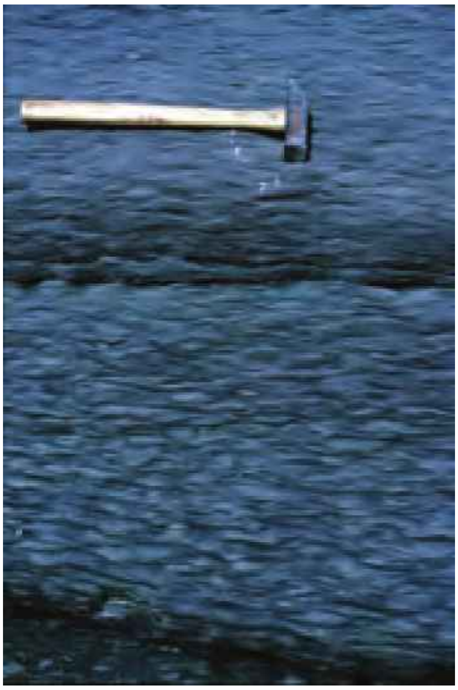

Figure 8.3 *Heterolithic (interbedded thin rippled) sandstones & mudstone wisps, Cobh, Co. Cork*

Common sedimentary structures are lamination, current ripples and cross-bedding (Study Box 8.1). Tidal currents and waves mostly produced the cross-bedding and ripples in these early Carboniferous rocks. Such heterolithic sandstones and mudstones are common, especially in south and west Cork where they form a sequence hundreds of metres thick, displayed in coastal outcrops, for example, at the Old Head of Kinsale, around Cork Harbour, and at the north end of Bantry Bay.

Study Box 8.1 Sedimentary Structures in shallow water sedimentary rocks

Figure 1. *Current ripples*

Ripple marks - can form in many different environments as a result of e.g. wind, currents and waves (Fig. 1). They may be different sizes and shapes, symmetrical or assymetrical. Formation of ripples depends on the velocity of the current; too slow or too fast and they will not form. At very high current velocities flat bedding forms.

Figure 2. *Planar cross-bedding*

Cross-bedding (see also Study Box 7.1) - take a cross-section through ripple marks and cross-bedding (cross-lamination) can be seen (Fig. 2). This is due to migration of ripple marks (Fig. 3a) and is a very common sedimentary structure. The current produces foreset laminae parallel to the lee side of the ripple and migrates in the direction of current flow (left to right in middle of Fig. 2). The angled beds in Fig.2 are planar, i.e. they are tabular in shape; some crossbeds are trough shaped. In tidal estuaries, reversing currents due to flood and ebb tides may produce chevron cross-bedding (Fig. 3b).

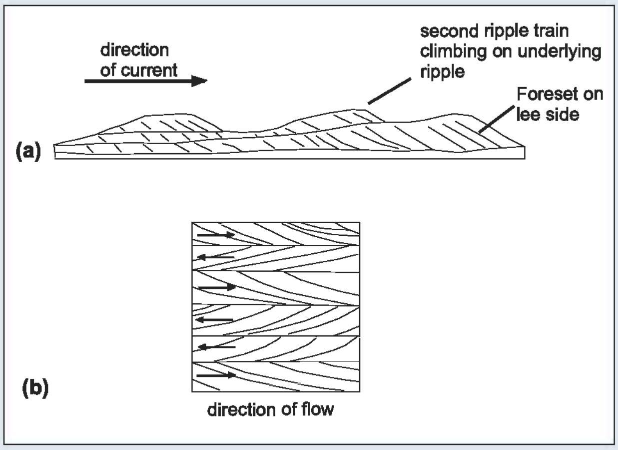

Figure 3 (a). *Migrating climbing ripples in cross-section,*
(b) *Chevron cross-bedding in reversing tidal currents*

The beach & shoreface environment
(Fig 4) shows many of these sedimentary features and burrows of animals living in the sand (Study Box 8.2) and shell beds washed up in the surf. Sand, which dries out, may be blown by the wind into cross-bedded dunes behind the beach (backshore). Sometimes tidal lagoons and marshes may be found inland of the beach and dune zones, as at Bull Island, in Dublin Bay and in south Wexford at Tacumshin Lake where a baymouth bar has almost cut off the lake from the sea. Beaches can vary from narrow and steeply shelving to very broad areas almost imperceptibly dipping seawards; they may be affected by high energy or relatively low energy regimes and are often modified by the effects of storms.

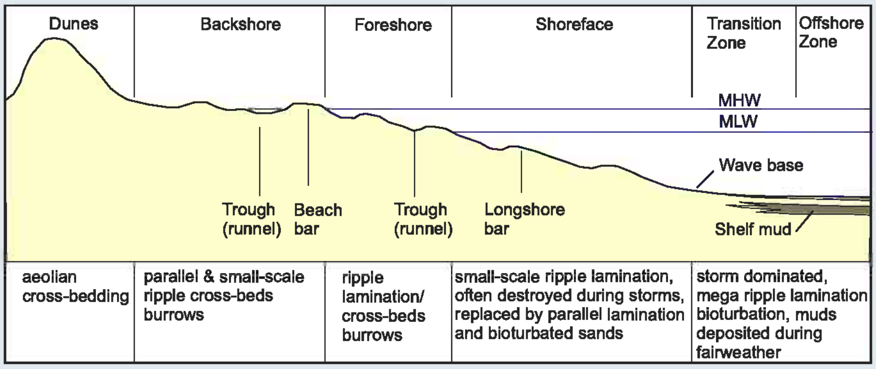

Figure 4. *Schematic profile of a typical beach*

Study Box 8.2 Trace fossils in shallow water sedimentary rocks

Trace fossils - many burrowing or grazing animals leave traces behind them in shallow water sediments which may then be preserved. The animal itself, which may or may not be soft bodied (i.e. without a hard shell), may never be preserved. Vertical burrows are produced by animals which live in the burrow and filter feed at the surface; as the sediment builds up so the animal moves up to compensate and the trace is preserved behind it. Traces of animals grazing on the sediment surface may be preserved if buried quickly.

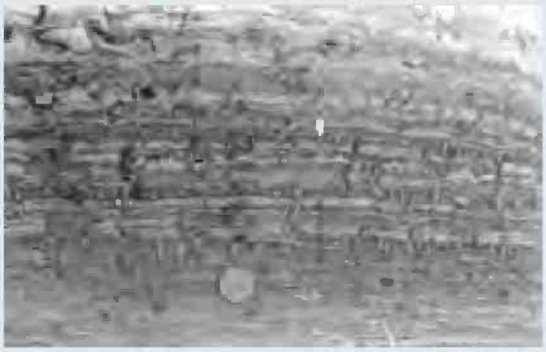

Figure 1. *Vertical burrows in Carboniferous sandstones from near Weston-Super-Mare, Somerset, note coin for scale.*

Figure 2. *Carboniferous grazing trail on sandstone bedding surface, Hook Head, Co. Wexford*

Figure 3. *Modern snail trails on beach at Umngazi, Eastern Cape, South Africa*

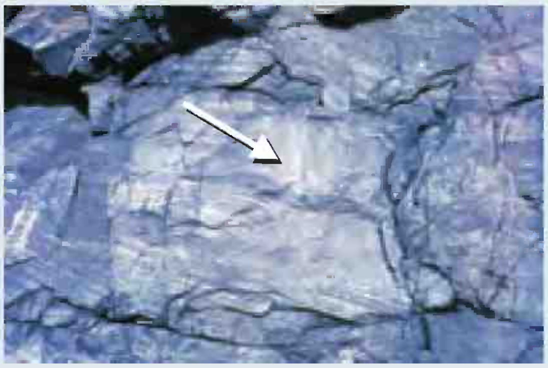

Figure 4. *A vertical burrow (see arrow) in cross-bedded dolomite. Hook Head, Co. Wexford*

Bioturbation - some sediments may be so disturbed by burrowing animals that most or all trace of the original bedding is destroyed. Bioturbation is common in the offshore and to a lesser extent in the shore-face zones of a beach profile.

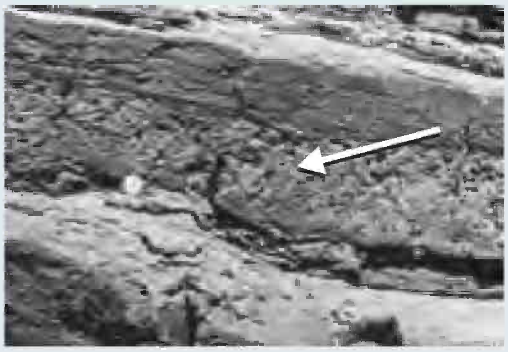

Figure 5. *Bioturbated Carboniferous sandstone (see arrow), Hook Head Co. Wexford*

LOWER CARBONIFEROUS - TROPICAL SHALLOW SEAS, LIMESTONE, KARST, MINES & QUARRIES.

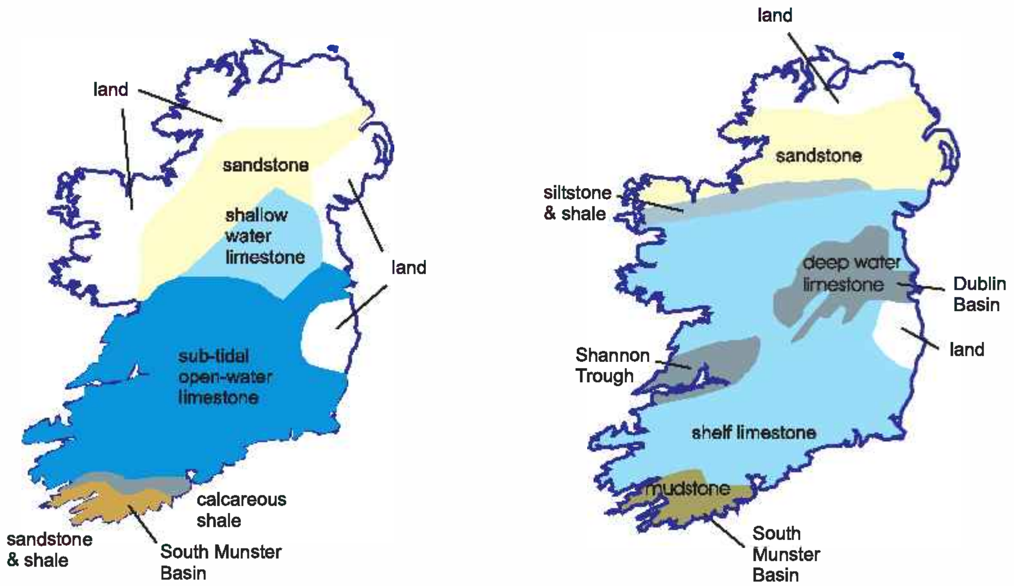

Figure 9.1 *(a) Palaeogeography in early Carboniferous Limestones times (about 350 million years ago); (b) later Carboniferous Limestone times about 330 million years ago.*

9.1 CARBONIFEROUS LIMESTONES & LIFE

By about 350 million years ago, the early Carboniferous sea covered most of Ireland south of a line from Galway City through Sligo to Belfast (Fig. 9.1a). This was a time of global rising sea-level. The encroaching sea deposited quartz-sands and mud near the shoreline, which are now lithified into sandstones and mudstones. Deeper water sands and mud continued to accumulate in the South Munster Basin as well (Fig. 9.1a). However, the central plain at this time was part of a broad shallow-water shelf sea where mainly muddy limestones formed. Later on this broad area of limestone deposition was broken up into shallow shelf areas and deep-water basinal areas (Fig. 9.1b). Relatively pure pale to medium-grey coarse-grained limestones dominated the shelf areas. The basins, on the other hand, contained very dark-grey fine-grained muddy limestones with interbedded calcareous mudstones. The formation of basins was related to faulting which was an early result of Variscan tectonics (see below). The climate and setting of limestone deposition was perhaps not unlike the Bahamas or the Persian Gulf today.

Limestones are largely biogenic sediments, that is, sediments derived from the breakdown and disintegration of calcareous shells of invertebrate animals. They are only rarely precipitated directly from sea-water (chemical sediments). They are usually formed in areas relatively free from influxes of sand and mud, where the shellfish can grow and live without being smothered by land-derived sediment. Areas of limestone development today are mostly in the tropics where the warm water abounds in fish, marine mammals invertebrates and plankton. In Carboniferous times, fish, including sharks were common, but usually only the teeth, made of phosphatic mineral, are preserved. The most abundant animals were invertebrate shellfish with shells made of calcium carbonate ($CaCO_3$).

These invertebrates included echinoderms such as crinoids (sea lilies), echinoids (sea-urchins), brachiopods (lampshells), bivalves (like mussels), bryozoans, corals, nautiloids (the pre-cursors to the ammonites), and trilobites (crustaceans) (Fig. 9.2). In addition there were many microscopic planktonic animals such as the single celled foraminifera, and many algae.


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Figure 9.2 *A selection of typical specimens of common Carboniferous fossils from the GSI fossil collection. The scale bar in all photos is graduated in mm. A,C. A tabulate colonial coral in longitudinal and section view. B. Another tabulate colonial coral. D. A large fish tooth, designed for crushing molluscs. E. Bivalve shells, moulds in shale. F. An internal mould of a bivalve in limestone. G, H. Two common forms of marine gastropod. I. A very large productid brachiopod, preserved as part shell, part internal mould. J. Three small solitary rugose corals. K. Two spiriferid brachiopods in limestone. L.Two goniatites, left preserved in three dimensions, showing the sutures between chambers and right, preserved flattened in shale. M. A common marine gastropod. N. The common internal cast of a lycopsid 'tree root'. O. Fragment of plant frond. P,Q. Coiled nautiloids. R. A collection of crinoid ossicles and plates. S. A trilobite pygidium ('tail' section). T. A cast of the leafy stem of a lycopsid 'tree'. U. The fine network of a fenestellid bryozoan.*

The invertebrate faunas were one of the most important constituents of the limestones formed in the Lower Carboniferous. Echinoderms (crinoids, echinoids, starfish etc.) in particular, contributed an enormous volume of calcareous grains to form limestones (Fig. 9.3).

Figure 9.3 *Weathered crinoidal Limestone*

The hard parts of the crinoid, for example, were made up of many pentagonal plates of calcium carbonate, that in life were held together by soft tissue, which rapidly decayed on the death of the animal. Currents and storm waves would quickly disperse the plates after death and deposit them like sand grains on the seafloor. In time these skeletal carbonate sands were cemented together by more calcium carbonate to form solid limestone. This cement came from waters saturated in calcium carbonate percolating through the unconsolidated sediment, and after deep burial under more sediment above, from solution along grain boundaries due to the pressure of the overlying rock. Such limestones are relatively coarse-grained and made up of grains in contact with each other with the pore spaces in between grains filled by cement.

Other limestones are fine-grained and made up principally of mud-sized carbonate ($CaCO_3$) material. Larger skeletal grains frequently 'float' in the fine-grained matrix (Fig. 9.4). Carbonate muds are often formed in shallow lagoons from the disagregation of calcareous algae and from faecal pellets of animals that live in the mud.

Figure 9.4 *Brachiopod shells 'floating' in a fine-grained limestone from Co. Carlow*

The most important fine-grained limestones in Ireland, however, are the 'Waulsortian Limestones', named after Waulsort in Belgium where they were first described. They formed mounds or banks often rising up from the sea-floor with steep sides. The steep sides are thought to have been maintained due to the binding effect of bacteria which produced a sticky mucous.

Figure 9.5 *Muleshoe Mound - a Waulsortian type carbonate mud-mound from New Mexico showing the exhumed mound shape*

The base of these banks could have been under as much as 300 m of water, but the tops were probably in the photic zone (perhaps less than 100 m depth). Similar banks have been described in the Carboniferous from as far away as the USA (Fig. 9.5). They are a good example of how the principle that 'the present is the key to the past' does not always work. There are no similar mounds today and earlier descriptions of them as 'reefs' are quite misleading, as they have no framework-building fauna like the Great Barrier Reef of Australia. The area around the Shannon Estuary, however, has the thickest development of them anywhere in the world. The banks in Ireland have mostly coalesced to form a continuous sheet of limestone, which can be traced from Cork northwards through the Shannon Estuary to the north midlands (Fig. 9.6). The Waulsortian Limestones are an important marker horizon for mineral exploration in Ireland (see below).

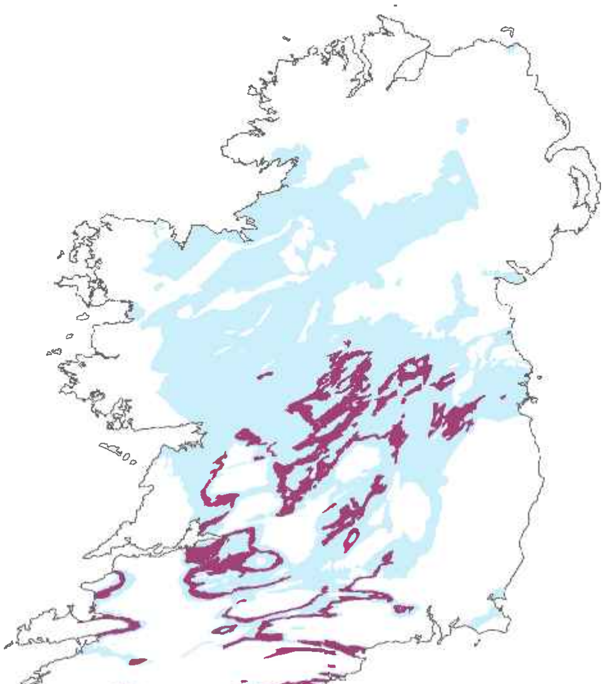


Figure 9.6 *The outcrop of the Carboniferous Limestone (blue) and the Waulsortian Limestones (Red)*

9.2 KARST

Limestones form some of the most striking landforms in Ireland, including the limestone pavements of the Burren, and the limestone cap to Benbulben Mountain in Co. Sligo.

One of the best places to see the Carboniferous limestones now is in the Burren, Co. Clare. Here the limestones are almost totally exposed at the surface and have hardly been disturbed by Earth movements, often dipping at 1-2^{O} or less from the horizontal. They have been gently buckled into open folds (anticlines and synclines). Individual bedding surfaces can be traced for miles showing that the limestones were deposited on a stable platform.

The Burren limestones are one of the best places in the world to study modern karst landscapes as well as ancient karst. The term Karst derives from the Karst area in Slovenia. It refers to landscapes developed due to the solution of limestones by rain and groundwater. (see Study Box 9.2). The limestones of the Burren are not porous, as the inter-granular spaces are filled by cement. However, groundwater is able to flow through the well-developed joints, both parallel to the bedding and at right angles to it. This is called permeability. The acid rainwater rapidly opens up the joints further often creating caves. Thus the groundwater flows through these rocks very rapidly. In consequence such areas are very vulnerable to groundwater pollution.

Clints and grikes (Study Box 9.2), caves, dolines, turloughs, sink holes and disappearing rivers can all be found in abundance in the Burren and surrounding limestone areas. The Cuilcagh Mountains of Cavan – Fermanagh contain another area of karst with the famous Marble Arch Caves.

Other limestones in Ireland, particularly the more pure limestones like the Waulsortian Limestones, are also subject to karstification and formation of caves, sink holes and other karst landforms. These features are often concealed beneath a cover of unconsolidated glacial deposits such as boulder clay. Aerial photographs are often used to find cavities close to the surface beneath glacial deposits. They often appear as small depressions in the fields. Good examples can be seen in east Cork where the Waulsortian limestones often contain caves which can be a hazard to industrial and infrastructural projects such as factories, pipelines and roads if not considered and investigated in the planning stage.

Within the limestones, examples of ancient Carboniferous karst are quite common. Shallow-water limestones frequently emerged above sea-level due to global sea-level changes related to the early phases of the Gondwana glaciation in the Carboniferous. These limestone surfaces were karstified by acidic rainwater and later covered by soil. The fossil soil horizons, are now represented by distinctive clay horizons lying on top of karstified limestone surfaces, which can be seen in the Burren and many other places. The clay horizons are called clay-wayboards (Fig. 9.7). Sometimes small rootlets can be seen penetrating down into the underlying limestone.

Figure 9.7 *Clay wayboard in Co. Clare resting on a Carboniferous karstic surface*

Some karstic hollows and caves may have been formed in the Mesozoic and others in the Tertiary Period. Relict tower karst can be seen in a few places such as Fenit, Co. Kerry (Fig. 9.8).

Figure 9.8 *Relict tower karst at Fenit, Co. Kerry*

Figure 9.9 *Tower karst from China*

Tower, or pinnacle karst, is well known from tropical areas today such as Indonesia and China (Fig. 9.9). Ireland's tower karst probably relates to karstification in the Tertiary Period (see section 15.3 & 15.4) after the chalk covering was stripped by erosion. Isolated limestone hills (hums; Fig. 9.10) are another common feature of tropical karstification found in Ireland (e.g. Rock of Dunamase). Dating many of these features, however, is difficult.

Figure 9.10 *Carboniferous hums, including Rock of Dunamase*

9.3 CARBONIFEROUS VOLCANOES

From time to time the deposition of limestones was interrupted by volcanic episodes. Volcanic activity was widespread in Lower Carboniferous times. Large volcanoes producing basaltic lava and ash existed south of Limerick City and at Croghan Hill, about 6 miles northeast of Tullamore, Co. Offaly. These volcanoes were located along lines of weakness in the Earth's crust (probably faults that were originally formed during the Caledonian Orogeny and reactivated in the Carboniferous). Smaller volcanic centres, intrusions and dykes and sills are quite common throughout the Lower Carboniferous rocks. The early eruptions in Limerick were explosive, reflecting seawater incursion into open vents, which gave rise to small cones of ash and volcanic breccias. Later eruption of basalt lava flowed more gently and cooled slowly sometimes developing columnar cooling joints (cf. The Giant's Causeway). Further explosive eruptions scattered wind blown ash over a wide area that can be identified as tuff bands within the limestones.

9.4 QUARRYING

The Carboniferous Limestone underlies more than half the country and is very much in demand as a source for building materials, road materials, and other uses such as beet sugar refining and agricultural ground lime for fertilising the land.

Because of high transport costs, quarries need to be sited as close to the point of use as possible. A distance of more than 20 – 30 km is usually considered uneconomical, but in some places cannot be avoided. Suitable limestones cannot always be found where you want them; there may be reasons why a particular site cannot be used, for example, if the area is in a national park or near a national monument. Quarries cannot now be sited closer than 250 m from the boundaries of a dwelling house to avoid dust and noise nuisance.

Figure 9.11 *Mungret Quarry, Limerick*

With the continuing spread of isolated rural single dwellings it is getting more and more difficult to find quarry sites. With increasing population and development, it is more important than ever to identify potential locations for aggregates and other Earth resources in order to avoid sterilisation of valuable resources. The current National Development Plan and National Spatial Strategy attempt to focus regional development together with county development plans to take account of future infrastructure, industrial and housing needs. Current minerals prospectivity mapping in the Geological Survey of Ireland attempts to identify those areas where there may be suitable Earth resources for commodities such as aggregates, so that County Councils can make informed planning decisions.

Quarry sites also have to take account of environmental factors, including the risk to groundwater contamination, noise and dust. If it is intended to quarry below the water table there will be additional costs for pumping and the potential effect on the groundwater aquifer will have to be investigated before quarrying is allowed.

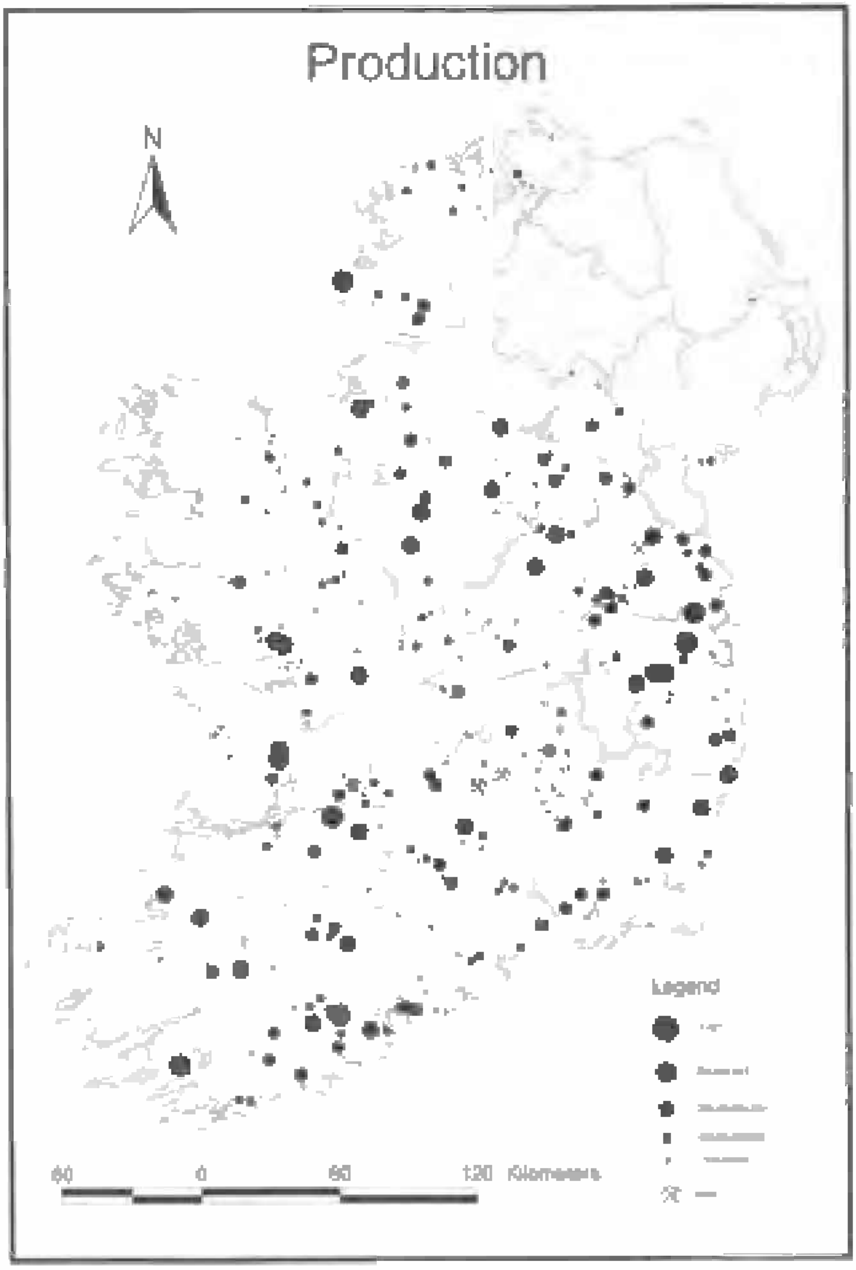


Figure 9.12 *Quarry production in Ireland*

Quarrying is a 2 billion euro/year industry in Ireland which has grown from 36 million tons in 1993 to110 million tons of aggregates extracted per annum in 2002 (including value added products such as concrete blocks, asphalt etc.) and accounts for 10% of all construction industry output (2000). A large part of that is sourced from the Carboniferous Limestone.

9.5 MINING

Most of the active mines and recently closed mines have sourced their zinc, lead, copper and silver from horizons within the Carboniferous Limestone. These predominantly zinc-lead deposits form one of the world's major ore-fields and share characteristics that have resulted in their mineralisation being called 'Irish Type'. They share the following features: -

a) They are found in the lowest, non-muddy limestone unit.

b) They are on or near to normal faults that formed conduits for upward migration of hot mineralised fluids.

c) Sphalerite ($Zn\ SO_4$) and galena ($PbSO_4$) are the principal sulphide ores.

d) They formed from metal bearing, moderately saline, slightly acidic, relatively sulphur poor fluids, which had a temperature of 120 - 280^{o}C.

Tara Mines, at Navan, is the largest zinc-lead mine in Europe, discovered in 1970. It is currently estimated to have 15 years of reserves left. However, they keep finding more ore, which may extend the life of the mine further, subject to the zinc price making extraction profitable. The ore is found in the Navan Group, an assemblage of shallow-water limestones at the base of the Carboniferous.

The deposit at Galmoy (Co. Laois) was discovered in 1986 and the nearby Lisheen mine (Co. Tipperary) was discovered in 1990; they are smaller deposits than the giant (80 million ton) Navan deposit. The ore in Galmoy and Lisheen is found at the base of the Waulsortian Limestones (Fig. 9.6); mapping the base of the Waulsortian limestones has proved a useful tool in mineral exploration. The former mine at Tynagh, Co. Galway, which started the modern base metals mining and exploration industry with its discovery in 1961, and the former mine at Silvermines, Co. Tipperary, both produced ore from the base of the Waulsortian Limestones.

Figure 9.13 *Aerial photo of Tara Mine, Navan*

Whereas the ore at Navan crops out at the surface, the Lisheen and Galmoy ores are not exposed. They were discovered by geophysical and geochemical techniques and proved by extensive drilling of the zinc-lead anomalies found. The ore concentrate is exported to smelters in Spain, Germany, Belgium and Finland for processing into metal. Even with the largest zinc mine in Europe, the volumes required to operate a smelter economically could not be justified in Ireland, particularly as there is an overcapacity of smelters world-wide.

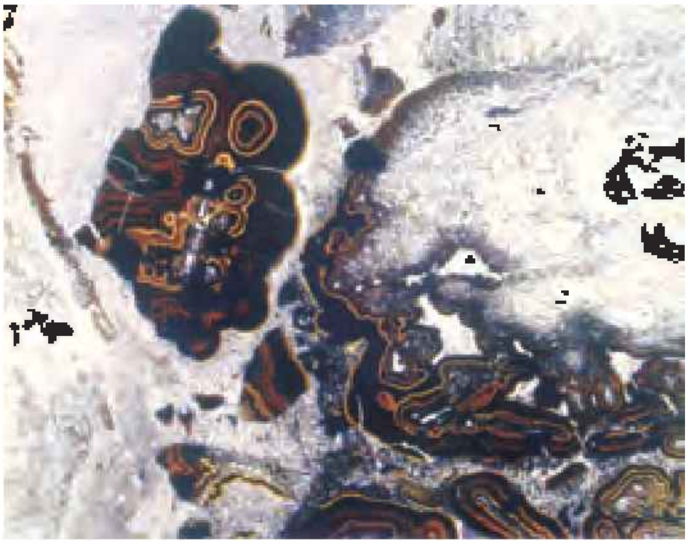


Figure 9.14 *Microscope picture in transmitted light of zinc ore (sphalerite) from Galmoy mine, Co. Kilkenny.*

Another mineral, barytes, is also associated with the zinc-lead mineralisation. Barytes is a very heavy white mineral (specific gravity of 4.5) used in the paints industry and as a drilling mud in oil well drilling. It was formerly open cast mined at Silvermines.

Study Box 9.1 Formation of Limestones

Limestones are made up of four constituents (1) biogenic skeletal grains, i.e. remains of calcareous shells of animals, (2) non-skeletal grains such as ooids (grains coated in layers of carbonate formed in shallow water under the influence of waves and tides) and peloids (mostly faecal pellets), (3) micrite, i.e. lime mud matrix, (4) cement deposited in intergranular pore space.

Limestones most often form in warm shallow tropical seas where there are abundant calcareous ($CaCO_3$) organisms and little land-derived sand or mud to dilute the build up of calcareous material. $CaCO_3$ is more soluble in cool water so is more easily deposited in the shells of invertebrates in warm waters. The shells from dead organisms accumulate and are broken up by wave and storm action and by grinding against each other.

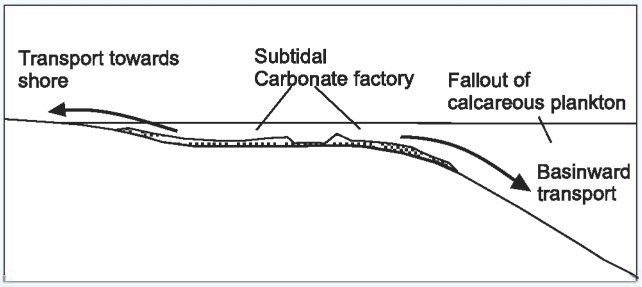


Figure 1. *Carbonate mud factory*

Many limestones are largely made up of fine-grained carbonate muds. These are often formed in shallow lagoons where the mud is produced by disaggregation of calcareous green algae. Some of it is in the form of faecal pellets derived from animals which chew there way through the sediment extracting microscopic food particles and some is produced by mechanical breakdown of larger grains. An over supply of carbonate mud is redistributed landwards to the tidal flats and seawards towards deeper water Figs 1, 2). This is happening today in the Bahamas.

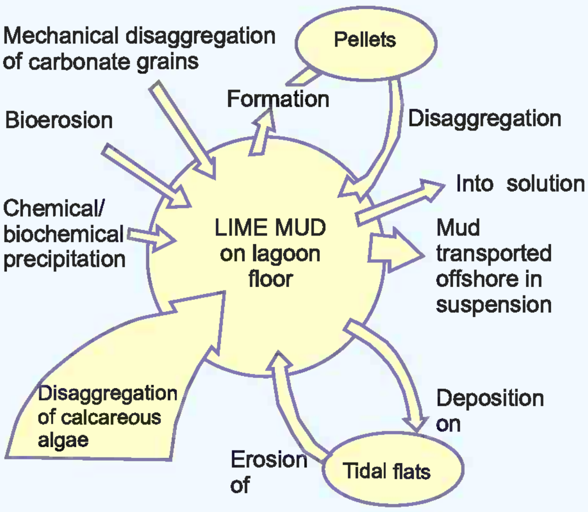


Figure 2. *Formation of carbonate mud*

Limestones can be classified in a number of ways but one of the most useful describes them according to whether the original components are supported by contact with each other (packstones & grainstones) or whether they 'float' in a fine-grained matrix (wackestones & mudstone) (Fig. 3).

Original components not bound together during deposition			
Contains lime mud			Lacks mud & is grain supported
Mud-supported		Grain-supported	
		mud & cement fills pore space	cement fills pore space
Mudstone	Wackestone	Packstone	Grainstone

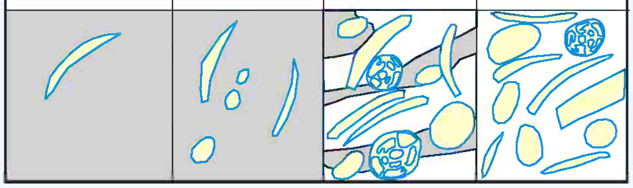


Figure 3. *Limestone classification (simplified)*

Study Box 9.2 Karst

A karst landscape is one where limestones have been partially dissolved by the percolation of acidified rainwater through the rocks. Rain (H_2O) combines with carbon dioxide (CO_2) to form carbonic acid $H_2O + CO_2 = H_2CO_3$ (Carbonic acid). The Structure of the limestone, (e.g. bedding planes and joints) will determine how karst develops (Fig. 1). The type of limestone will also influence whether karst landforms develop. A pure limestone, rather than a muddy limestone, will dissolve more easily as will a limestone not protected by an impervious cap-rock from the percolating groundwater.

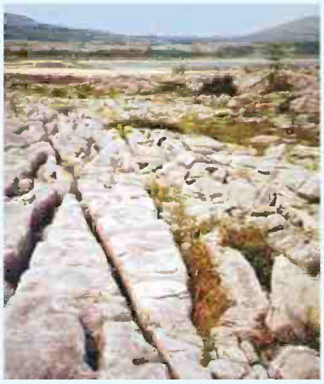


Figure 1. *Clints & grikes*

Clints and grikes (Fig. 1) are formed by the opening up of joints at the surface by acidified rainwater. The grikes are enlarged depressions along the rock joint and the clint is the upstanding area of limestone left between the clints.

Turloughs (Fig. 2) are seasonal lakes in which the water rises and falls according to the condition of the water table due to interconnections with subsurface karstic groundwater flow.

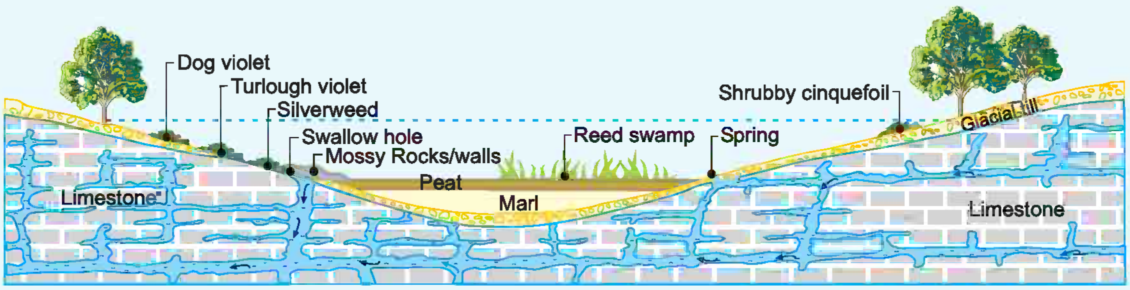


Figure 2. *Cross-section of a turlough*

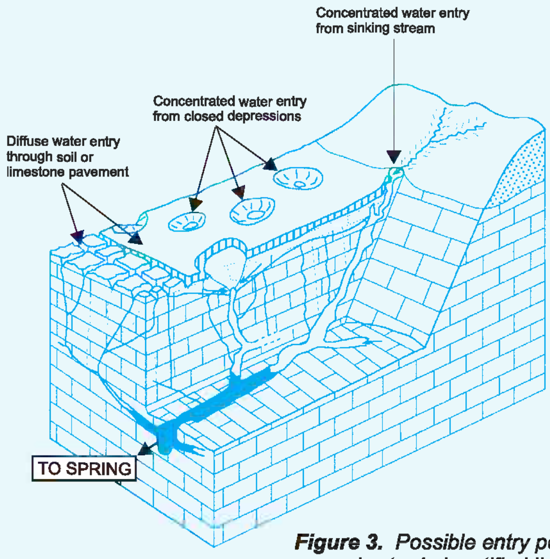


Figure 3. *Possible entry points for pollution of groundwater in karstified limestone*

Karstic landscapes are very prone to groundwater contamination as water flows through the opened up joints very quickly (Fig. 3). Groundwater vulnerability maps attempt to identify areas most vulnerable to pollution and allow intelligent decision making for planning the location of developments close to such sites.

10 UPPER CARBONIFEROUS - DELTAS & COAL SWAMPS, AND THE VARISCAN OROGENY

The Upper Carboniferous is divided into three principal units: - the Namurian at the bottom followed by the Westphalian and then the Stephanian. In Ireland the lower part of the Namurian is dominated by deep-water shales and turbidites followed by shallow-water deltaic sandstones. The top part of the Namurian and the lower part of the Westphalian contain coal measures. The higher parts of the Westphalian are rare in Ireland and there are no Stephanian rocks; they were either never deposited, or were removed by erosion.

Figure 10.1 *Black shales overlain by thick sandstones at Foynes, Co. Limerick*

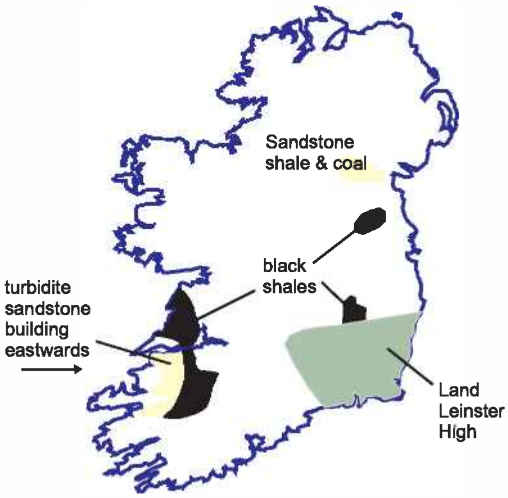


Figure 10.2 *Palaeogeography in early Namurian times*

10.1 THE NAMURIAN

The change from limestones to black shales happened relatively quickly and is best seen around the Shannon Estuary in counties Limerick and Clare (Figs 10.1, 10.2). The topmost limestone formations record a gradually deepening sea with shallow-water limestones succeeded by limestone turbidites and storm deposits. The sharp change to black shales is probably due to (1) tectonic uplift, to supply the clastic sediment, and (2) rapid subsidence in the Shannon Trough to accommodate the sediment and allow for further deepening of the sea. The black shales contain a rather restricted fauna of goniatites that swam in the open ocean (pelagic). Fossiliferous beds alternate with barren beds. The restricted nature of the fauna suggests that the trough (and other Namurian basins in Britain and Ireland) was unconnected to, or had only restricted access to open ocean and perhaps had a reduced salinity level. Periodically, global changes in sea-level allowed a more normal marine fauna to encroach from the open ocean. These eustatic sea-level changes are attributed to the glaciation in the southern hemisphere covering much of the Gondwana supercontinent (see below). Eustatic sea-level changes due to glaciation started in Dinantian (Early Carboniferous) times and increased in size throughout the Namurian and Westphalian.

In West Clare, around Loop Head, there are thick sandstones in the early Namurian sequence. These sandstones were transported from shallower water into the basin by turbidity currents triggered by earthquakes. Finer grained material remained in suspension for a time so that the sandstones now show graded bedding, fining upwards.

Tectonic subsidence gradually slowed, and sea-level began to fall globally. Deep-water, basinal sandstones and shales were replaced by shallow-water, deltaic sandstones and shales (Study Box 10.1). Ireland took on the appearance of the Mississippi Delta as it is today. Again the best places to see these deltaic rocks are on the coast of West Clare, at the Cliffs of Moher and the Bridges of Ross.

10.2 WESTPHALIAN

The Westphalian was the time of coal deposition in Ireland and across much of Europe and the USA. Coalfields in Ireland are limited in extent (Fig. 10.3). A typical coal measure sequence consists of repeating cycles starting at the base with a marine shale overlain in turn by non-marine shale, sandstone, siltstone, shale, seat-earth (fossil soil) and coal (Study Box 10.2). As with the Namurian rocks of West Clare, this sequence was produced by a delta where the sedimentation built up towards the sea surface and then became land as relative sea level fell. Vegetation grew in what is now the seat-earth and then accumulated to be buried by the next marine shale as global eustatic sea-level rise allowed the sea to encroach once again and start a new cycle. The climate was tropical and wet and the water-table was near, or at the surface, so that the trees fell into a swamp and were buried, when they died, to form a peaty deposit. Following deep burial and millions of years this vegetation was transformed into coal.

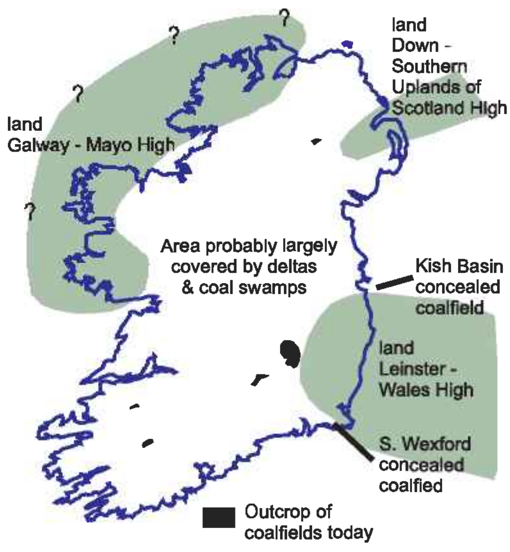


Figure 10.3 *Palaeogeography in early Westphalian times*

The coal in the Castlecomer area (Leinster Coalfield) is of anthracite grade. It is much harder than the bituminous and semi-bituminous coals worked, for example, in the Midlands of England; this is due to deeper burial under overlying rocks, with the result that it was heated to a relatively high (metamorphic) temperature. The temperature increases by at least 1.5^0 for every 100 m depth below the Earth's surface, due to heat production within the mantle from the decay of radioactive minerals. Anthracite is of a higher calorific value than bituminous coal but is harder to burn.

The coals formerly worked in Ireland are all from the Namurian or early part of the Westphalian. Evidence suggests that a great thickness of later sediments of later Westphalian age were deposited and then eroded. In south Co. Wexford there is a small deeply buried coalfield containing thin coals of latest Westphalian age; there are also younger Westphalian deposits in basins in the Irish Sea (Kish Basin) which have been assessed for exploitation by gasification *in situ*.

Figure 10.4 *An open cast coal pit in Scotland*

The last significant working mines closed in 1989 (Leinster) and 1990 (Arigna). The principal producing coalfields in Westphalian strata were in the Castlecomer and Slieveardagh areas of Counties Kilkenny, Carlow and Tipperary. Coals of Namurian age were worked from the Slieve Anieran and Arigna coalfields of Co. Leitrim and Ballycastle and Coalisland (Dungannon), in Northern Ireland. Irish coalfields have thin coal seams, which are relatively uneconomic to work, particularly as they are often faulted. Traditionally much of the coal required was imported from Britain or Poland where seams were thicker and bituminous house coal available (Fig. 10.4). At the present time coal is imported for power generation at Moneypoint, on the Shannon Estuary, from Australia. Cheap open-cast extraction and the advantage of bulk transportation can compete more favourably than with European production.

10.3 CARBONIFEROUS GLACIATION

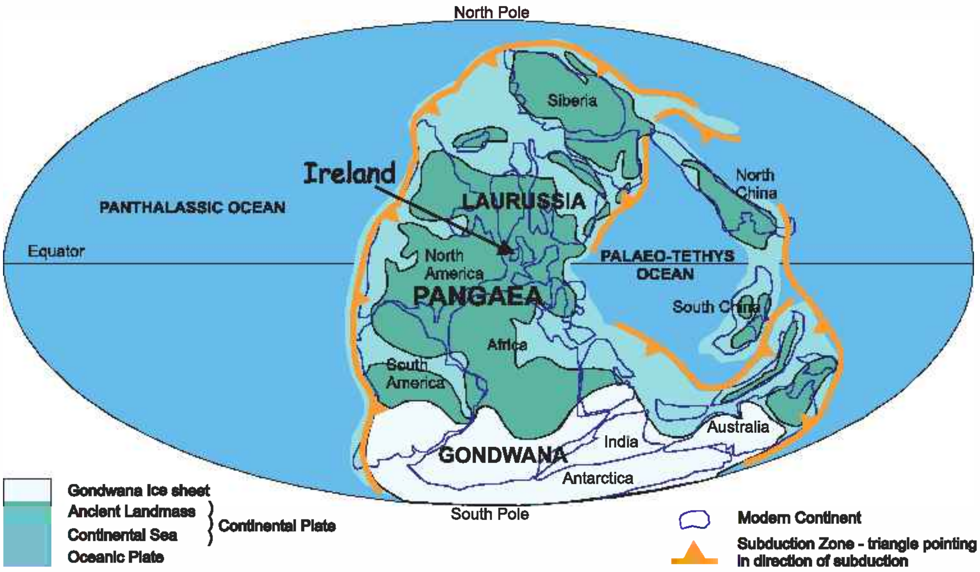


Figure 10.5 *Plate reconstruction for the Upper Carboniferous (306 million years ago)*

Global changes in sea-level at the end of the Carboniferous can be attributed to global ice house conditions in the southern hemisphere (see Chapter 15) with repeated glaciations and interglacial periods. Glacial sediments have been identified in South America, South Africa and Australia, from this time, when they formed part of the ancient super-continent of Pangea - Gondwanaland centred over the South Pole. Global sea-levels fell by about 60 m (about half the sea-level fall during the Quaternary Glaciation) as water was trapped in ice-sheets. Low quantities of carbon dioxide (CO_2) in the atmosphere were balanced by high carbon concentrations in coal swamps and high levels of oxygen due to photosynthesis of Carboniferous plants.

10.4 THE VARISCAN OROGENY (LATE CARBONIFEROUS – PERMIAN)

The late Carboniferous and early Permian was another time of tectonic activity and mountain building in Ireland, known as the Variscan Orogeny (also sometimes called the Armorican or Hercynian after other areas in Europe). There is no suture across Ireland representing the plate tectonic boundaries at this time, like the earlier Caledonian Orogeny Iapetus Suture. This is because plate boundaries lay far to the south in Germany and Spain (Fig. 10.6). Ireland at the end of the Carboniferous was on the edge of the orogenic belt but still close enough for mountains to be formed in Munster.

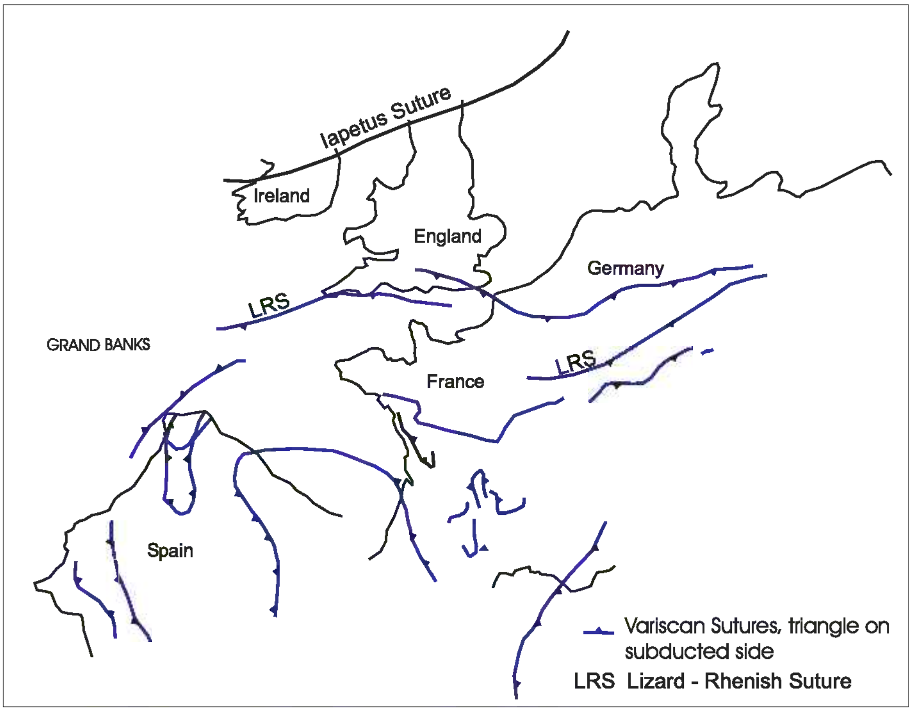


Figure 10.6 *Sketch of the main Variscan tectonic features in northwest Europe*

The first effects of Variscan tectonics were felt in Cornwall and Germany during the early Devonian, where the Lizard – Rhenish Suture (Fig. 10.6) probably marks the site of a residual early Devonian ocean basin. The effects in Ireland led to the deposition of the vast quantities of sands and mud that formed the Old Red Sandstone in the Munster Basin (section 7.3.1, Fig. 10.7). These were the erosion products of the wearing down of the Caledonian Mountains to the north. Further Variscan tectonics in early to mid-Carboniferous times resulted in flexing of the Earth's crust under Ireland resulting in the formation of a large sedimentary basin – the Shannon Trough, and further north, uplift in the Dublin Basin causing faulting, unconformities, erosion and the deposition of conglomerates (Fig.10.7).

All this activity before the main phase of subduction and orogenic mountain building in the late Carboniferous, demonstrates that tectonic activity is always going on due to plate movements and subduction. To an extent the separation of the Caledonian and Variscan orogenic events is artificial.

The ridge and valley province of Munster is the result of Variscan mountain building. Here the rocks were folded into broad open anticlines and synclines with a wavelength of several kilometres. The anticlines are now, for the most part, the ridges and mountains, formed by the sandstones and mudstones of the Devonian Old Red

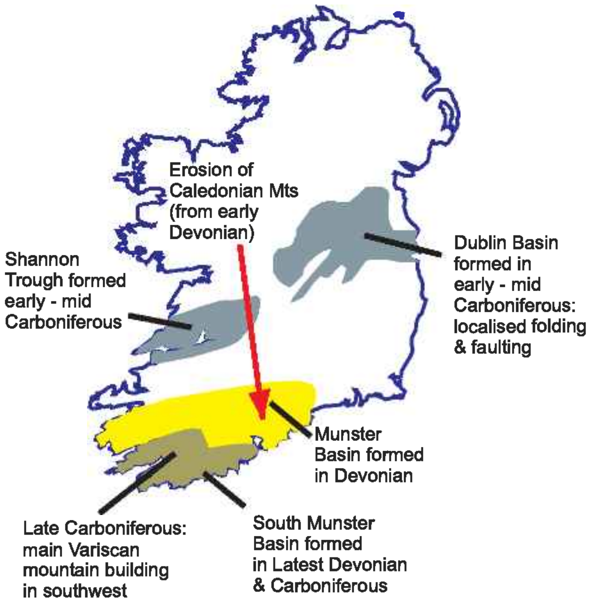


Figure 10.7 *Effects of early Variscan tectonics in Ireland*

Sandstone. The synclines are now the valleys, which are floored by rocks of Carboniferous age; limestones in the east from Youghal to Castlebridge in the Lee and Bride Valleys and in the Cloyne and Carrigaline areas; sandstones and mudstones further south and west towards Bantry, Skibbereen and limestones again at Kenmare.

The tectonic strain was great enough for the finer grained rocks to have a slaty cleavage imposed on them (Fig. 10.8) and the coarser rocks a spaced cleavage. Faulting was also quite significant with many reverse and oblique or wrench faults releasing the strain along what are now the valley margins. One such reverse fault (high angle thrust) can be traced from Killarney to Mallow. Northwest – southeast cross faults are also very common. Folding took place first with ductile (plastic) deformation being replaced by brittle failure and consequent faulting when the limits of ductility had been crossed. Tectonic shortening, the amount of horizontal compression, of south Munster, as shown by the folding, cleavage and faulting, was probably as much as 30 - 40 %.

Figure 10.8 *Cleavage (vertical) and bedding (dipping to the left), Fountainstown, Co. Cork*

Figure 10.9 *Variscan folds at Loughshinny, Co. Dublin*

Variscan tectonics gradually diminish in intensity northwards, but there are still thrusts in the Galty Mountains as significant as the Killarney – Mallow fault zone, cleavage continues generally for some 70 km north of Killarney, and can be seen as far north as Loughshinny, Co. Dublin where there are spectacular Variscan folds (Figs 10.9, 10.10).

In south Munster the trend of the Variscan folds and faults is east – west to east-northeast – west-southwest in West Cork and Kerry. This trend is perpendicular to the main axis of Variscan strain, which pushed from the south northwards. In the midlands, however, Variscan faulting tends to take on a more northeast – southwest Caledonian trend, with older faults being reactivated.

It is difficult to separate deformation in the northern part of Ireland that is Variscan from later Mesozoic or Tertiary events; many of the faults in the northern half of the country appear to be normal faults in extension rather than compression, as would be expected of Variscan structures, another example of how earlier tectonic events influenced future events.

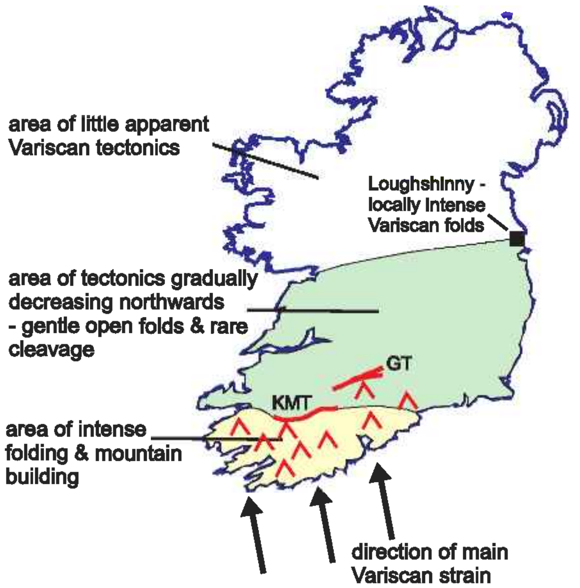


Figure 10.10 *Effects of main phase of Variscan tectonics (KMT – Killarney Mallow Thrust Fault; GT - Galtee & Slievenamuck Thrust Faults)*

Unlike earlier orogenies, the Variscan, in Ireland, was far enough away from the centre of the event for metamorphism to be slight. There are no granites intruded in Ireland contemporaneous with end Carboniferous Variscan deformation to bake the surrounding rocks, as was the case with the Dartmoor and Bodmin granites in Devon and Cornwall. The most obvious low-grade metamorphic event was the imposition of the slaty cleavage and formation of slates in some of the finer grained Carboniferous rocks. In addition the temperature was raised sufficiently to turn the coals in Leinster into anthracite.

Study Box 10.1 Deltas

Deltas form when a river carries more sediment into the sea than the sea can redistribute by currents. The sediment then accumulates at the river mouth and builds out into the sea. The ideal delta is cone shaped. There may be several channels carrying sediment seawards forming a 'bird's foot' shaped delta; channels frequently migrate laterally as the sediment deposited builds up and spills over the delta flood-plain to find another route to the sea. The delta is divided into the Upper Delta Plain, the Lower Delta Plain, and the Delta Front (Fig. 1). The upper part of the delta plain is above the level of salt-water intrusion and is dominated by fluvial processes (Study Box 7.1), whereas the lower delta plain, is affected by wave and tidal processes and the seaward end is submerged. The delta front is the leading active edge of the delta and extends down slope into the offshore marine zone.

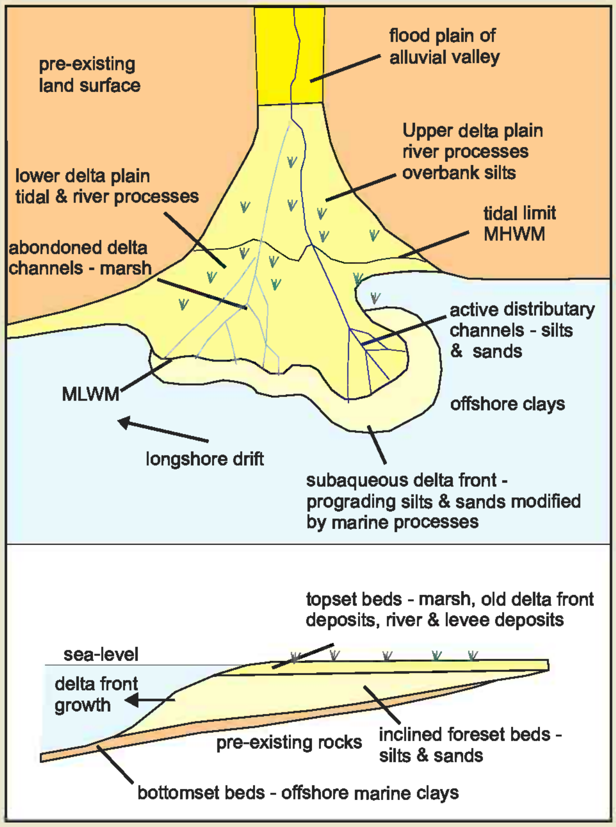


Figure 1. *Schematic model and cross-section through a river dominated delta advancing into the sea*

The sides of the main distributary channels are often marked by levees; these are coarse-grained sand deposits built up by overbank flooding. They become finer grained further away from the channel. In times of flooding the levees are sometimes breached and large quantities of sediment are deposited in the areas between the channels as crevasse splays (Study Box 7.1). Sometimes silt is deposited in the interfluves by sheet-flow of sediment laden waters over the channel banks. These interfluves (flood plain) often contain shallow lakes and gradually build up into marshland.

The growth and shape of deltas are affected by many factors such as the velocity of the water entering the sea, density contrasts between the fresh river water and the salt seawater, water depth and bottom slope seaward of the river mouth. Deltas are also modified by fluvial and marine (wave and tidal) processes. Deltas dominated by fluvial processes include the Mississippi, Po, and Danube; wave action dominates the Rhone, Niger, and Orinoco deltas and tidal processes the Ganges-Brahmaputra and Mekong delta. Other smaller deltas sometimes form in lakes and so are not affected by marine processes. Other important factors include the rate of subsidence, and climate. The rate of subsidence is affected by a combination of tectonic forces, compaction of the sediment and eustatic sea-level changes.

Climate - Deltas in a humid wet tropical environment will enable the growth of dense vegetation, which traps more sediment and then leads to the deposition of peat in a miry swamp with the eventual formation of lignite and coal (Study Box 10.2). In an arid climate, however, whether hot or cold, vegetative cover plays a minor role and aeolian processes are more important on the delta plain.

Deltas often cover a vast area. The Ganges delta, for example, covers an area the size of Scotland. Such areas have been colonised and farmed for millenia, for example in the Nile delta, as the sands and silts are very fertile. People have learnt to live with the prospect of flooding as an inevitable result of living in an unstable environment.

Study Box 10.2 Coal Measure Cycles

Coal is found in beds which form part of a recurring sequence of sediments (a **cyclothem**). The cyclothems were deposited in a wet swampy tropical deltaic environment. Coal is formed from lush vegetation and trees. The vegetation died and fell into a swamp or marsh to form peat, which was later compressed and converted into coal under the weight of overlying sediments and heat generated from the Earth's mantle under deep burial. In Leinster the coal was buried to a considerable depth resulting in mild metamorphism during the Variscan Orogeny which heated it enough to form a harder form of coal called anthracite which has a greater calorific value.

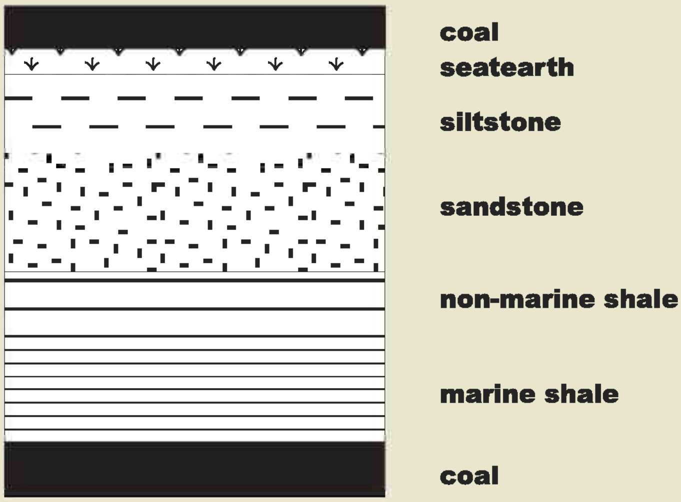


Figure 1. The ideal coal measure cyclothem

A typical coal measure cyclothem started with a rise in sea-level which flooded the delta and deposited marine shale. Parts of the lower delta plain were eroded by the sea. The relative sea-level rise was due to a combination of tectonic movements, compression of the deltaic sediments and / or a global rise in sea-level. Global sea-level changes are attributed to the melting of ice-sheets covering the continent of Gondwana in the southern hemisphere during the Upper Carboniferous.

Sea-level then began to drop, marine shale was followed by non-marine shale deposited in lagoons on the delta plain. Later sandstone and siltstone was deposited in incised valleys cut into the delta plain by the river channels as a result of the river adjusting to a lower base-level (see Study Box 15.1), and as mouth bars at the delta front.

With further sea-level falls more shale was deposited in a shallowing sequence. As the delta rose above sea-level, soil developed (seat-earth) on the interfluves (areas in between the main distributary channels of the river). Finally peat was deposited in a marsh. It is unusual to find a complete coal measure cyclothem at any one place due to distributary channels switching position eroding older sediments. Channels often became choked with debris and were bypassed; the original channel was then colonised by trees and vegetation that eventually became coal.

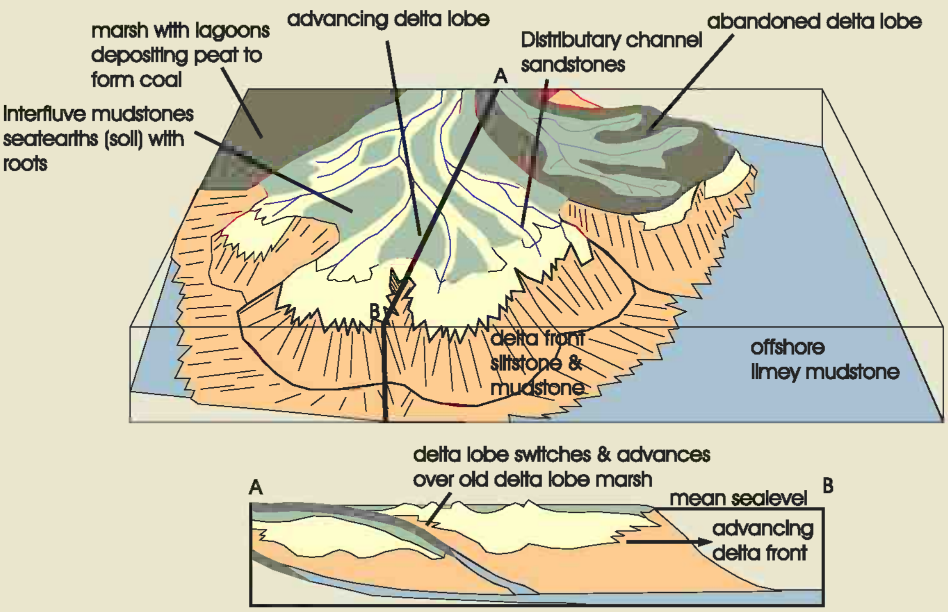


Figure 2. Schematic model of a coal measure delta lobe switch

11 PERMO-TRIASSIC - 'NEW RED SANDSTONE' DESERT

11.1 THE LOWER PERMIAN - ARID CLIMATE & COARSE BRECCIAS

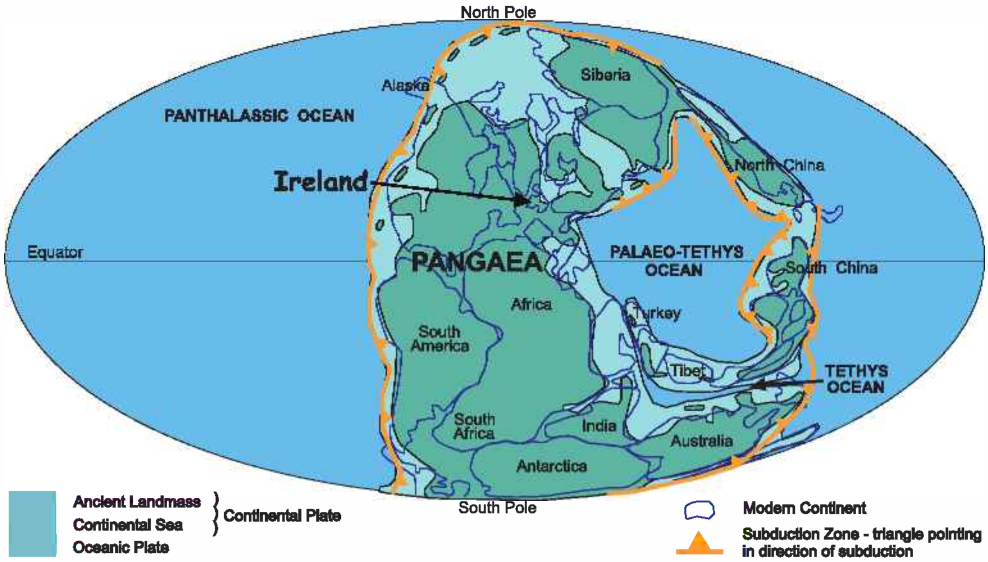


Figure 11.1 *Plate reconstruction for the Late Permian*

By the beginning of the Permian, around 298 million years ago, Ireland lay just north of the equator as a low-lying arid desert area on the newly amalgamating supercontinent of Pangaea (Fig. 11.1). This 'New Red Sandstone' desert environment, similar to the rocky deserts and dune sand-seas of modern-day Saudi Arabia, dominated the Irish landscape.

Permo-Triassic rocks are preserved on land mainly in the northeast, because here thick layers of rock have been protected from erosion by the covering of Tertiary basalt lavas in Counties Antrim and Derry (see Chapter 13).

A ridge of Precambrian rocks, the Highland Border Ridge, existed from the Permian and throughout Mesozoic times, from Scotland southwestwards across the northeast Antrim coast (Torr Head) to the Sperrin Mountains. Great thicknesses of Permian sediment accumulated to the northwest and southeast of this ridge, in small subsiding basins that were produced by down-faulted graben with steep faulted scarps. Weathering and erosion in the hot dry climate cut deeply into the steep slopes of bare rock, producing screes at the foot of the hills that lithified to form breccias. Only a few metres of these breccias are now exposed at Cultra on the east side of Belfast Lough, but over 300 m are known to be present in the Strangford Basin. Similar conglomerates and coarse sandstones are found at the base of the Permian sequence north of Armagh.

The early Permian landscape was also marked by volcanic eruptions in the northeast, as shown by lavas and tuffs overlying breccias in a borehole near Larne. They have been correlated with similar volcanics in Ayrshire, Scotland, and form part of a large volcanic province covering the northwestern part of Europe.

11.2 THE UPPER PERMIAN - EVAPORITES & MINING

Climatic conditions changed quite abruptly in Upper Permian times, when the desert areas were flooded by an incursion of the warm shallow inland sea, the Bakevellia Sea (Fig. 11.2), which lay to the west of the Irish landmass. Repeated flooding and evaporation throughout the period resulted in the cyclic deposition of limestone, shale and salt layers. Magnesian limestone (dolomite) and evaporites accumulated in the north, while massive

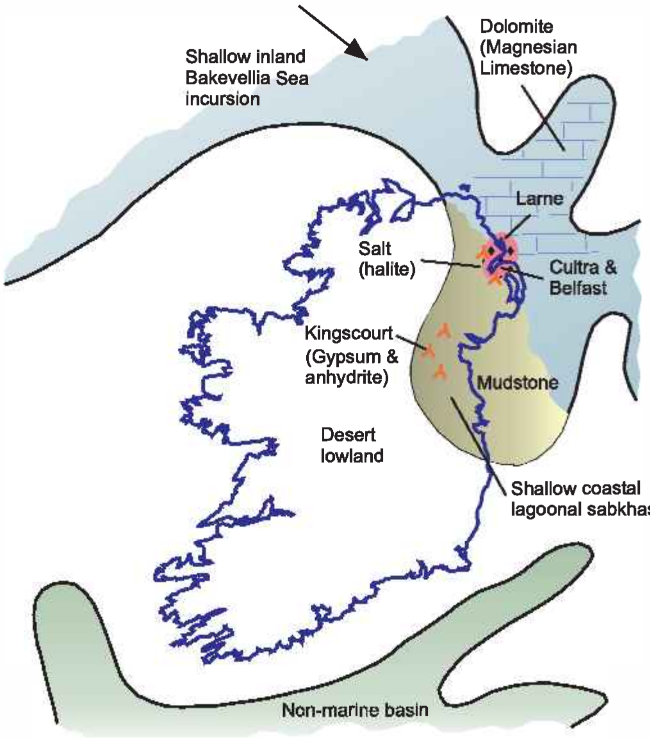


Figure 11.2 *Permian palaeogeography*

gypsum deposits formed in shallow coastal sabkha lagoons to the south (Study Box 11.1). Similar cyclic evaporite deposition was taking place in the large inland Zechstein Sea, which stretched from northeast England as far as northern Germany and Poland.

Figure 11.3 *The Magnesian Limestone at Cultra, Belfast Lough*

The magnesian limestone is found only in boreholes and at a few outcrops. On the foreshore at Cultra (Fig. 11.3) it is quite fossiliferous. Most abundant is a fossil bivalve shell called *Bakevellia*, named after the sea in which it lived. This rock was used for the cornerstones in the building of Carrickfergus Castle.

The gypsum deposits are well known from the Kingscourt outlier straddling counties Cavan, Monaghan and Meath. Here two main gypsum and anhydrite layers (totalling about 45 m in thickness) are interbedded with red and purple mudstones of uppermost Permian age. In the past, gypsum has been mined from both horizons at Kingscourt in several underground operations and is currently extracted from the upper layer in a major opencast pit at Knocknacran in County Monaghan (Figs 11.4, 11.5). The gypsum is used for plaster and plasterboard manufacture in nearby Kingscourt and is transported nationally for cement and filler production. More than 5 million tons of gypsum has been extracted during a period of over 50 years.

Further east, the extensive salt beds that formed from evaporation of the Zechstein Sea, are also commercially important. Across North Germany and the North Sea they form an impermeable seal to the gas trapped in underlying sandstones (see Study Box 13.1) and at Stassfurt, the salt deposits contain valuable potash. Near Krakow in Poland, a salt layer of around 3,500 m thickness has been mined and a network of buildings, roads and railways excavated deep underground.

Figure 11.4 *The open pit at Knocknacran, Kingscourt Gypsum Mines*

Figure 11.5 *The entrance to the underground gypsum mine at Kingscourt.*

Gradually, lagoonal conditions took over the whole sea basin area and extensive beds of anhydrite were formed between layers of marl and siltstone. Cycles of oolitic limestone and sabkha-type gypsum, anhydrite and halite (rock salt) have been recognised in a borehole at Belfast Harbour. Another borehole near Larne penetrated 113 m of halite in Upper Permian marls. The Upper Permian sedimentary sequence is continuous with overlying Triassic sandstones in the Larne borehole and at Kingscourt, but on the basis of different plant spore species, the Permian-Triassic boundary has been placed within these marls.

11.3 TRIASSIC PERIOD

The start of the Triassic period (250 - 203 million years ago) saw a return to terrestrial desert conditions with the deposition of finer-grained sandstones and siltstones in a variety of settings such as alluvial fans and low-energy rivers. In the Armagh area, basal conglomerates and coarse red sandstones were probably deposited as alluvial fans. Some of the sand deposits were transported by the wind and shaped into dunes. These sands, now compacted into sandstones, have been worked for Belfast's building stones. At one of these workings near Newtownards, the fossil footprint of a Triassic reptile was discovered on a sandstone bedding plane. Thick red-brown sandstones were later deposited in sedimentary basins that were probably partly fault-controlled, as in the north Antrim and Larne areas.

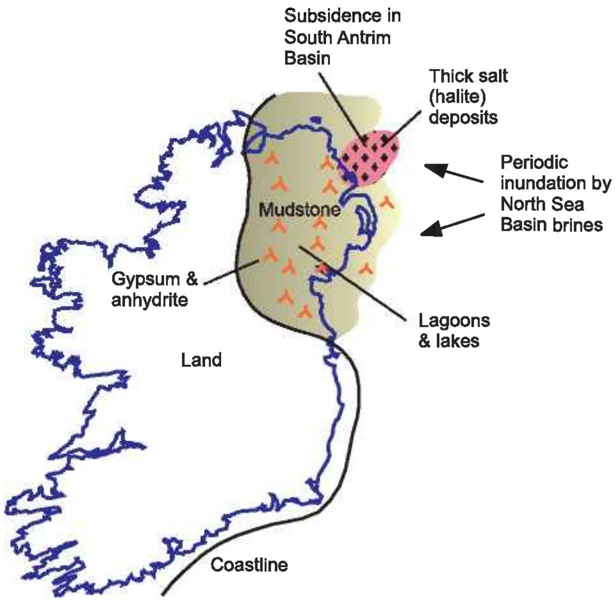


Figure 11.6 *Lower Triassic palaeogeography*

Later in the Triassic, fluviatile conditions again gave way to a lagoonal or lacustrinal setting (Fig. 11.6). In the Armagh area, red and green marls and mudstones are interbedded with thin veins of gypsum that originated from periodic incursions of sea brines from the north. Great thicknesses of sediment and evaporites accumulated in the subsiding Larne Basin, including more than 400 m of halite (rock salt). First discovered in the nineteenth century from boreholes and mine shafts during the search for coal, the South Antrim Salt Field probably extends farther northeastward than the known area between Larne and Carrickfergus. A thinner seam of rock salt is currently being worked from Kilroot mine on the north side of Belfast Lough.

A distinctive pale-green marl, in which marine fish remains have been found in other parts of the British Isles, has been found in uppermost Triassic mudstones from boreholes in the Larne Basin area. This represents the beginning of a change from continental conditions to the marine transgression that continued into the Jurassic Period.

On the map, a small patch of Permo-Trias can be seen in the Ballyteige Bay area on the South Wexford coast. These red conglomerates and sandstones of continental origin are known only from boreholes where they rest unconformably on Carboniferous rocks; they are most likely Triassic in age, as are similar rocks found offshore in the Celtic Sea Basin.

Seismic evidence suggests that there are around 2000 m of Triassic beds (with evaporites in the upper part) in the Porcupine, northern Irish and Irish Sea basins, with thinner sequences present in the Celtic Sea basins (Figure 12.4).

11.4 THE END OF AN ERA

The Permian - Triassic boundary marks the end of the Palaeozoic era ('Old Life') and the beginning of the Mesozoic era ('Middle Life'). However, the continental sequences deposited in Ireland at this time lack a clear faunal and sedimentary break.

Permian sea-life saw an increase in the variety of echinoderms (sea-urchins), brachiopods and ammonites. The belemnites (cigar-shaped internal shell of a squid-like animal) were rising in importance from their Upper Carboniferous origin. On land, many reptile groups had evolved, including the widespread mammal-like theraspids. However, the end of the Permian Period was marked by the most dramatic global extinction to date (see below), leading to vastly different faunal characteristics in the Mesozoic Era as vacated ecological niches were filled by new forms. By the beginning of the Triassic Period, about 75% of amphibian and over 80% of reptile families had disappeared and there were great reductions in marine animal groups, especially amongst the trilobites, corals, echinoderms and brachiopods.

The ammonites barely survived into the Triassic, but their descendants produced spectacular evolutionary radiations. A great variety of advanced bony fish types (teleosts) had evolved by the Upper Triassic and a dramatic radiation of the reptiles (which arose in the Lower Carboniferous) also marked the beginning of the

Mesozoic. This included the first dinosaurs to walk on land, marine reptiles such as the ichthyosaurs and by the end of the Triassic, the gliding pterosaur reptiles. By this time, the first true mammals had also appeared.

Many contributory factors have been mooted for the Permo-Triassic extinctions, which were originally believed to have taken place over a period of about 10 million years. These include a reduction in surface temperatures as a result of extensive airborne ash from massive volcanic eruptions, perhaps even leading to glaciation and related falls in sea-level. A recent theory invokes a two-phase temperature rise initiated by the Siberian trap eruptions (Study Box 14.1) over a relatively short span of 80,000 years (as indicated by the fossil record in Greenland rocks). A slow temperature increase of about 5° C would have produced warming of bottom waters, triggering the release of huge 'frozen' methane gas deposits from around the continental shelves. The addition of vast amounts of methane to the atmosphere could have further boosted temperatures. It is estimated that a 6° C rise in global warming was sufficient to wipe out 95% of species on land and in the sea. While life would take thousands of years to recover, one important survivor into the new age of dinosaurs was a mammal-like reptile, *Listrosaurus*, the ancestor of mammals and ultimately, man.

Study Box 11.1 Desert Processes - Evaporites

Evaporites, or salt deposits, are the most important chemically formed rocks, produced by precipitation and crystallisation from saturated solutions in a variety of environments, from salt lakes and sabkhas to partially isolated marine basins. The most abundant large-scale evaporites found in the geological past and at present-day, are rock salt (or halite; NaCl), anhydrite ($CaSO_4$) and gypsum ($CaSO_4.2H_2O$), which form predominantly in marine settings.

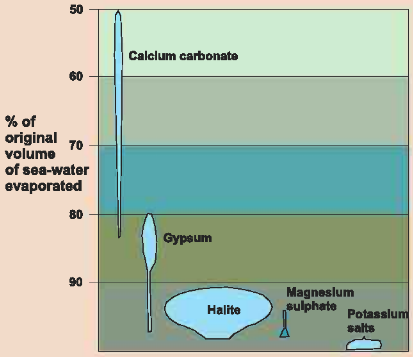


***Figure 1.** The order of precipitation of evaporite minerals as seawater evaporates, and their relative proportions.*

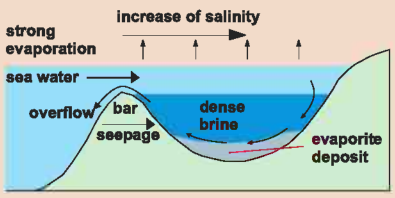


***Figure 2.** Evaporite model for a restricted marine basin*

Seawater evaporation causes precipitation of an ordered sequence of minerals (Fig. 1), from gypsum (when seawater concentration rises to nearly four times its normal salinity of 3.5%), to halite, to magnesium sulphate and finally to potassium salts (at 90 times normal seawater concentration). Complete evaporation of a 1000m column of seawater would produce only a relatively thin evaporite layer.

To explain the substantial thicknesses of ancient evaporites, a large isolated or highly restricted basin must be repeatedly replenished with large volumes of seawater that are evaporated before the basinal brines become diluted. The length of time that the seawater is resident in the evaporating basin, determines the brine salinity and the mineralogy of the evaporite. Seepage through a permeable barrier is the most likely means of seawater inflow, and this can be seen happening today at Lake Macleod in Western Australia (Fig. 2).

Ancient marine evaporites are preserved throughout the geological column from Cambrian times to the present day, and can be of economic importance, especially when great thicknesses are present (see Section 11.2). For instance, the Permian salt deposits of western Texas and New Mexico have been proved to be about 3,500 m thick.

Evaporites easily recrystallise and can become very mobile under pressure. These slowly rising 'intrusions', known as salt domes, push up the overlying sediments and are of economic significance in creating potential oil and gas traps (see Study Box 13.1).

Thick ancient evaporates formed in the centre of basins, but all present-day marine evaporites are found in a marginal basin setting. Evaporites can precipitate from brines at any depth, but most form in shallow settings where evaporation is highly effective. This can be in both marine and non-marine fed salt lakes and lagoons, which are called salinas.

The high rates of evaporation and low rainfall in the desert are ideal for the accumulation and preservation of evaporites. Intermontane basins are often the site of temporary, or playa, lakes that are fed by short-lived torrential streams and shallow sheetfloods carrying mudflows. The lakes usually last a few days or weeks, before total evaporation leaves behind a flat lake bed of clay (a playa deposit). The clay is encrusted with salts precipitated during evaporation, their composition depending on the type of dissolved salts in the water, in turn reflecting the kind of rock from which they were eroded. Desert streams tend to carry high concentrations of dissolved salts through repeated cycles of evaporation and dissolution.

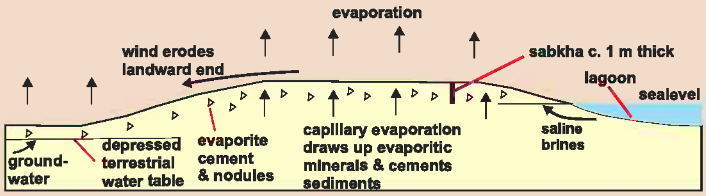


***Figure 3.** Modern sabkha model for evaporite deposition*

The margins of deserts sometimes stretch as far as the coastline, as seen today on the Persian Gulf shore, where large flat areas above high-water level (supra-tidal), become encrusted with sandy material, salt, gypsum and calcium carbonate. These flats, known as sabkhas, are formed by evaporation of brines drawn up from the shallow seawater table, depositing crystalline salts at the surface.

12 JURASSIC - SHALLOW SEAS & OFFSHORE BASINS

12.1 LIAS CLAYS & FOSSILS

By the start of the Jurassic Period (203 - 144 million years ago) the area of Ireland and Britain had drifted to about 40° north of the equator (Fig. 12.1). Pangaea continued to break up into Gondwana and Laurasia, the developing rift between North America and northwest Africa marking the opening of the future Atlantic. The Jurassic climate probably resembled that of present-day humid countries with monsoon-type summers. Warm, shallow seas repeatedly covered parts of Ireland and Britain, as the underlying continental crust continued to warp and rift.

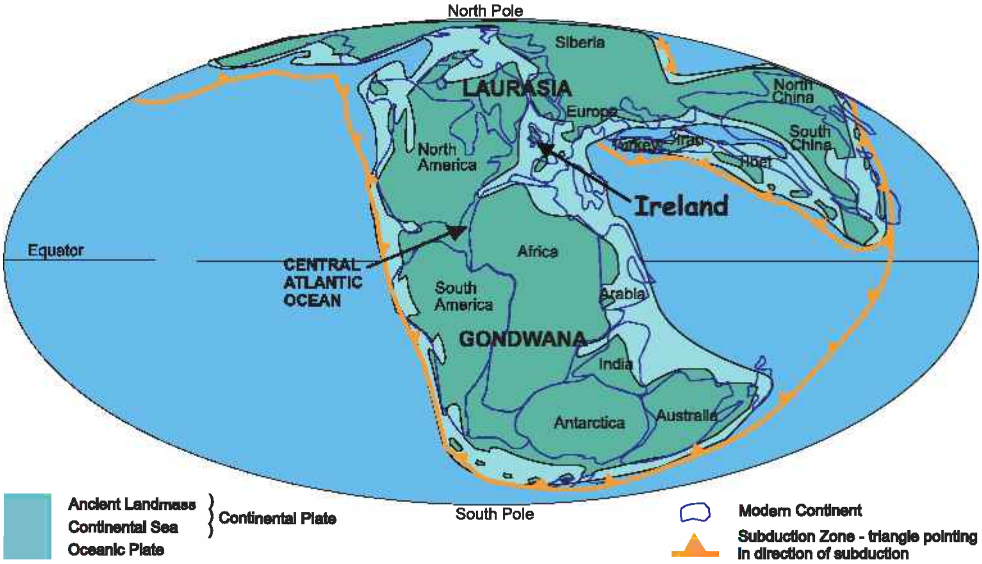


Figure 12.1 *Plate reconstruction for the early Jurassic*

While much of Ireland was land in Jurassic times (Fig. 12.2), in the early Jurassic (Lias), warm shallow seas covered northeastern Ireland (and possibly the east and south), most of England and the Hebridean side of Scotland. In Ireland, Liassic sediments are now preserved only in the northeast, due to the protective covering of Tertiary Antrim basalts, and in offshore areas (see below). The absence of deposits elsewhere may be due to non-deposition on land or to subsequent erosion.

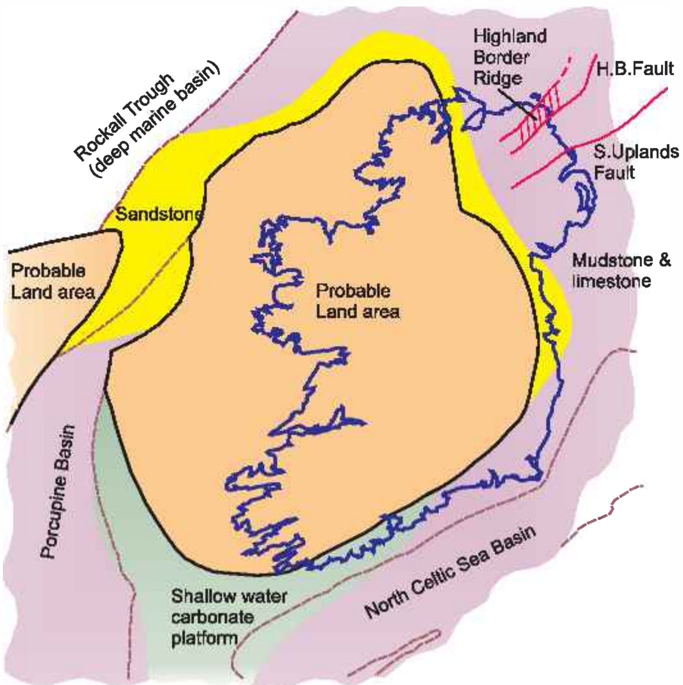


Figure 12.2 *Lower Jurassic palaeogeography*

Liassic mudstones and limestones are visible today along the foreshore near Larne, where they are over 100 m thick and rich in ammonite fossils. Along the coast northwards from Larne to Garron Point, the impervious mudstones cause regular landslides and mudflows due to their instability during times of excessive rainfall. Inland, the Lias is known from boreholes on the east side of Lough Neagh. The rock becomes much thicker north of the Highland Border Ridge (Section 11.1), for example around Portrush.

Figure 12.3 *Ammonites from Liassic limestone, near Larne*

At Garron Point, the fossil remains of part of a large marine reptile were found in mudstones before the site was built over. In England, Liassic clays are famous for their ammonite and reptile fossils at Lyme Regis on the Dorset coast and at Whitby in Yorkshire. The rapidly evolving and abundant ammonites have been used to date the Jurassic rocks.

12.2 MIDDLE & UPPER JURASSIC ROCKS

Middle and Upper Jurassic rocks are scarcely represented onshore in Ireland, as it was a land area at this time. One small pocket of Middle Jurassic clay, probably deposited in a lake, has been preserved east of Cork in a palaeokarstic hollow in the Carboniferous limestone. Shallow marine clays of late Jurassic or Cretaceous age found in a borehole in south County Kilkenny mark the edge of the thick Mesozoic sediment fill accumulating at this time in basins to the southeast of Ireland (see below, Fig. 12.4). The muddy sediments of the Lias and the uppermost Jurassic, laid down on the western seaboard and in the Celtic Sea basins, would later become the source rocks for oil and gas deposits.

In eastern and southern Britain, interchanging marine and terrestrial environments throughout the Jurassic produced a variety of rock types. Middle Jurassic oolitic limestone forms the impressive sweep of Cotswold Hills from Cheltenham southwards to Bath and Bristol where it is used as an attractive creamy-coloured building stone. Cotswold-type stone was frequently imported into Ireland and used in churches and other buildings for decorative features, due to its softness and ease of carving. Dundry stone from Bristol was used for this purpose in St Canice's Cathedral in Kilkenny.

In the Upper Jurassic, thin limestones developed, which can be seen on the Dorset coast at Portland and Purbeck. Portland Stone, a massive limestone containing bivalves and ammonites has been used as a masonry stone, for example in the facings of most of the principal Georgian buildings in Dublin.

The end of the Jurassic saw the continued breakup of Pangaea with the narrow Central Atlantic Ocean beginning to separate eastern North America from Africa. The North Atlantic Ocean made its first, unsuccessful, attempt to open, causing a rift to form along the line of the North Sea. This North Sea rift would mark another site of important future oilfields (Chapter 13).

12.3 JURASSIC LIFE

The shallow seas contained a rich fauna of ammonites, bivalves, fish and reptiles such as the plesiosaurs. The ammonites diversified rapidly and when one group died out, another soon replaced it. Coral and sponge reefs were well developed in deeper southern waters of the Tethys Ocean (separating Laurasia from the southern Gondwanan continents) and periodically colonised the shallower seas to the north. On land, reptiles, dominated by the dinosaurs, were roaming across a warm, wet and richly vegetated landscape. The pterodactyls developed flight and by the end of the Jurassic, the first true bird, *Archaeopterix*, its feathers modified from scales, had evolved. The early mammals, that had first appeared in the Upper Triassic, were small and relatively inconspicuous.

12.4 MESOZOIC BASIN DEVELOPMENT - THE FOUNDATION FOR OIL & GAS

Although poorly represented onshore, Mesozoic rocks are present in thick sequences offshore, for example in the Porcupine Basin to the west, and in the Celtic Sea basins to the south of Ireland (Figure 12.4), where seismic surveys have revealed a sedimentary thickness of 3 - 9 km. These rifted basins formed mainly from tensional forces during Permian to Cretaceous times, related to the beginning of North Atlantic opening and breakup of Pangaea.

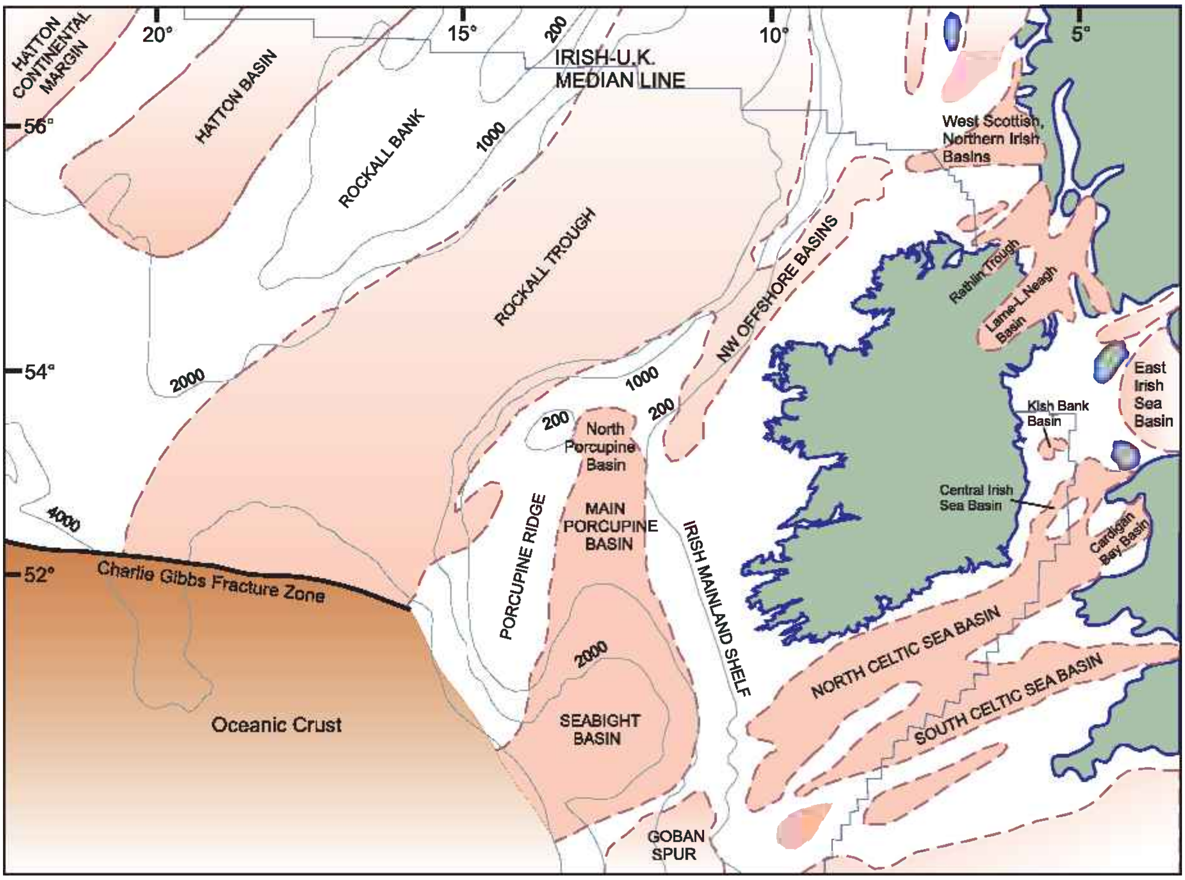


Figure 12.4 *Mesozoic Basins off the coast of Ireland*

In Jurassic times, muddy Liassic sediments were uniformly deposited throughout the Celtic Sea and Irish Sea basins, but were mostly confined to the North Porcupine Basin on the western seaboard. Middle Jurassic subsidence resulted in a thick accumulation of sediments within the basins around southern Ireland, their absence from the northern Irish and Irish Sea basin areas probably resulting from later erosion. A withdrawal of the sea in late Jurassic times led to shallow marine sedimentation in the North Celtic Sea and Porcupine basins, and mostly non-deposition across the northern Irish and Irish Sea basins. Contemporaneous tectonic activity, resulting in faulting, uplift and erosion, produced a major unconformity in the Celtic Sea and western seaboard basins. The general absence of post-Lower Jurassic rocks from the Irish Sea basins is probably due to late Jurassic and Tertiary periods of erosion.

13 CRETACEOUS - WHITE CHALK, BLACK OIL

13.1 GREENSAND & CHALK

The Cretaceous Period lasted from 144 - 65 million years ago, a time when the American and Eurasian plates diverged and formed a rift that became the North Atlantic Ocean (Fig. 13.1). During the early Cretaceous, most of the landmass of Ireland remained above sea-level apart from a shallow sea incursion over parts of Antrim that resulted in deposition of the 'Hibernian Greensand Formation' (Fig. 13.2). The mineral glauconite, which is known to form only in shallow-water, gives the sand grains their green coating. Numerous fossils of an oyster-like bivalve are found in this green sandstone, which can be seen in the Lagan Valley and on Islandmagee in County Antrim.

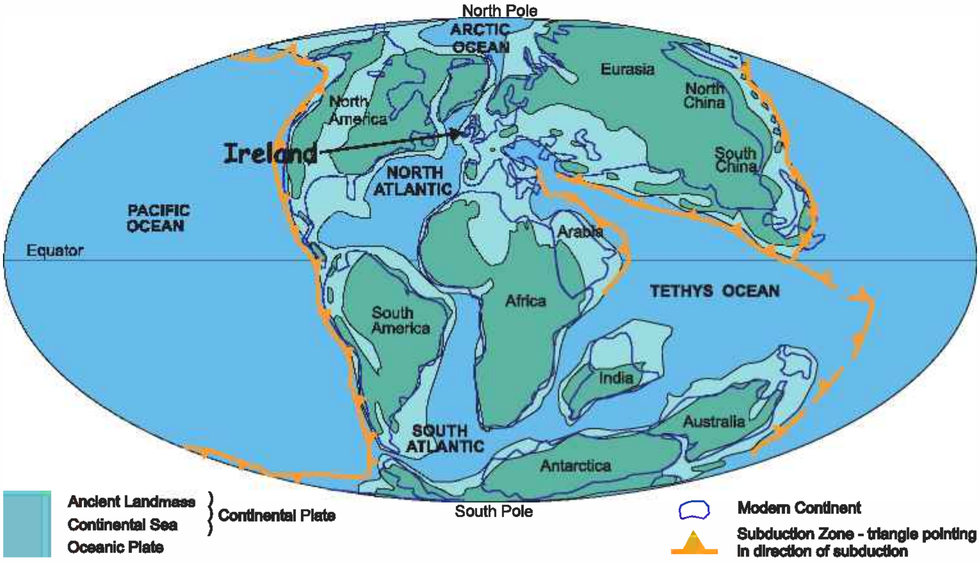


Figure 13.1 *Plate reconstruction for the late Cretaceous*

However, some terrestrial sediments (for example, of fluvial and deltaic type) were deposited southeast of the present coastline in the Celtic Sea basins during Lower Cretaceous times. These are now preserved as important reservoir rocks in the Kinsale gas field area. Terrestrial conditions later reached northeastern Ireland, resulting in widespread erosion of much of the greensand (now marked by a major unconformity).

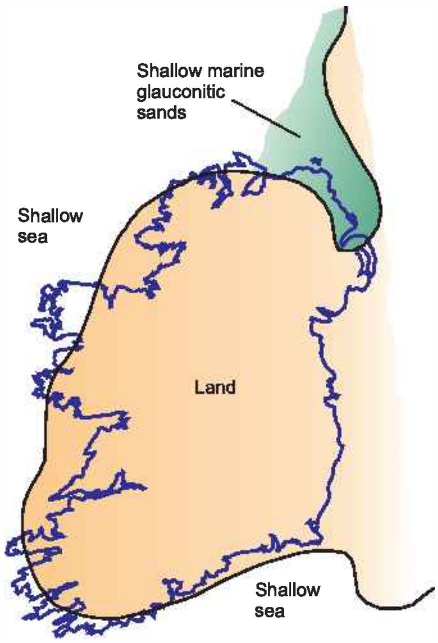


Figure 13.2 *Lower Cretaceous palaeogeography*

It was not until Upper Cretaceous times that marine deposition resumed, with more greensands, conglomerates and a distinctive white limestone. A warm shallow sea covered the Irish landmass (Fig. 13.3), and sea-levels worldwide are estimated to have been at their highest in all Palaeozoic and Mesozoic times (about 300 m above present levels).

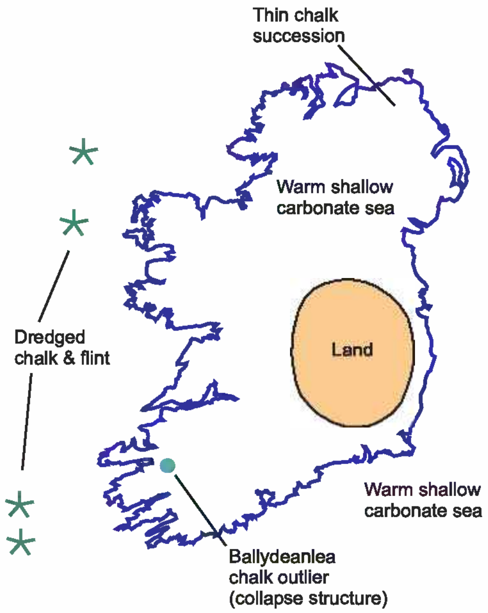


Figure 13.3 *Upper Cretaceous palaeogeography*

Northwest Europe lay in subtropical latitudes at about 35º north (Fig. 13.1). Microscopic single-celled organisms with internal calcareous discs, called coccoliths, inhabited the sea. These accumulated after death in vast thicknesses on the sea-floor, becoming gradually compressed to produce a white limestone, or chalk. The chalk is also characterised by the fossilised remains of larger marine creatures, such as echinoids (sea-urchins), belemnites, ammonites and fish, including sharks.

The Ulster White Limestone can be seen forming prominent cliffs around the Antrim and Causeway coast, in scarp faces east of Limavady, Co. Derry and outcropping in hills west and north of Belfast.

Figure 13.4 *The Ulster White Limestone along the Antrim coast, overlain by basalt.*

A soft, porous chalk makes up the 'White Cliffs of Dover' in southern England, but the Ulster chalk is much harder due to the filling of its pore space with calcite (probably from circulating hot groundwater) and to extreme compaction by the overlying basalt lavas.

Flint (a variety of silica that breaks with a conchoidal or shell-like fracture) occurs throughout the chalk, mostly as nodular accretions of the siliceous spicules of sponges, but also in bands precipitated by later silica-rich groundwaters. This secondary silicification sometimes filled the interior space of an echinoid shell after the decay of its soft parts, producing a detailed internal mould in flint.

Extensive quarrying of the chalk was carried out at Ballintoy and Larrybane Head, to be burnt in limekilns for use as agricultural lime.

Outside the Antrim area, chalk has been found in few areas. It occurs in a pocket of Carboniferous rocks near Killarney, County Kerry, where it is thought to have fallen, as soft seafloor sediment, into an underlying collapsed cavern. Chalk with flints has been dredged up off the coasts of Kerry and Connemara and thick chalk sections are also known in the Celtic Sea basins. This indicates that the late Cretaceous sea covered much of Ireland and its continental shelf. The present day absence of chalk from southern parts of Ireland is believed to have been due to rapid erosion of the soft chalk sediment, following uplift and marine regression at the end of the Cretaceous and in the early Tertiary. This tectonic activity also created potential traps for oil and gas within the Mesozoic sediments of the offshore basins (Study Box 13.1). In the north, the chalk was preserved by the protective cap formed by the outpouring of Tertiary basalt lavas across the chalk landscape (Chapter 14).

13.2 THE CRETACEOUS - TERTIARY (K/T) BOUNDARY, FAUNAS & MASS EXTINCTIONS

During the Cretaceous, the marine coccoliths reached their peak, the foraminifera (another group of micro-organisms) became important and the teleost fish started their spectacular radiation of ‘modern’ types. On land, the dinosaurs remained dominant. The flowering plants (angiosperms, which may have originated as early as the Triassic) rose to dominance in mid-Cretaceous times. Their dramatic spread was paralleled by that of butterflies and bees.

The Cretaceous - Tertiary boundary (known as the K/T boundary) was marked, quite abruptly in geological terms, by mass extinctions both on land (most notably the dinosaurs) and in the sea (for example, ammonites and belemnites). This global catastrophe is thought to have resulted from a combination of rapid changes in climate, due to sea-level fall, volcanic activity (the vast Deccan trap eruptions were happening at this time; see Study Box 14.1) or an asteroid collision with Earth. In the Gulf of Mexico, the 180 km wide Chicxulub impact crater, made by an asteroid about 10 km in diameter, has been cited as evidence for this, although there has been some recent debate over whether the crater pre-dates the K/T event. The resulting fireball and darkness caused by airborne debris from such an impact, however, would certainly have produced a global temperature drop large enough to devastate marine and terrestrial environments.

The marine fossil record at the K/T boundary shows an abundance of chalk sea faunas (although some species were already in decline) terminated by a thin clay layer of iridium-rich impact debris that is found worldwide at this level. The overlying Tertiary strata show an impoverished fauna and a gradual introduction of new species. Almost all (90%) Cretaceous foraminifera died out at the boundary and the succeeding Tertiary forms are less diverse. It is likely that some species had already started to die out due to a climatic change, and that an impact or other catastrophic ‘event’ precipitated the mass extinction.

13.3 HYDROCARBON SETTING & PETROLEUM EXPLORATION IN IRELAND

Oil and gas reservoirs have been found in rocks of various ages in Irish territory. The source material for the hydrocarbons originated from organic material within Jurassic shales, and trapping mechanisms were created by late Cretaceous tectonic activity. The recognition of promising traps in offshore basins through geophysical survey and subsequent drilling, led to the first commercial hydrocarbon production in Ireland from the Kinsale gas field (Fig. 13.5).

In the past, exploration activity in Ireland was hindered by a relative lack of success and by high costs. Prior to the Continental Shelf Act in 1968, which defined Irish jurisdiction of offshore waters, exploration had been confined onshore with little result. However, between 1969 and 1998, a total of 130 wells were drilled in offshore basins, most of them in the Celtic Sea area. The success of Kinsale (see below) in the 1970s resulted in increased offshore exploration activity, and the First Round of Licensing in 1975 offered exploration ‘blocks’ on the continental shelf to oil companies. This was followed by drilling in the Fastnet and Kish Bank basins and in the deeper basins off the west coast of Ireland (Fig. 13.5).

In the relatively deep Porcupine Trough (Fig. 13.5), several non-commercial oil flows were tested in the late 1970s, including from the Connemara field, which though estimated to contain 40 million barrels of oil in Jurassic sandstones, was later deemed uneconomic, due mainly to water depth. During the 1980s, decreased oil prices, high exploration costs and the paucity of commercial discoveries resulted in many exploration companies pulling out of Ireland. In 1992 a new licensing system, reflecting the environmental and technological problems of the frontier exploration area, was introduced to attract outside investors. Since the start of Frontier Licensing rounds in 1993, the majority of licences have been awarded in blocks off the west coast.

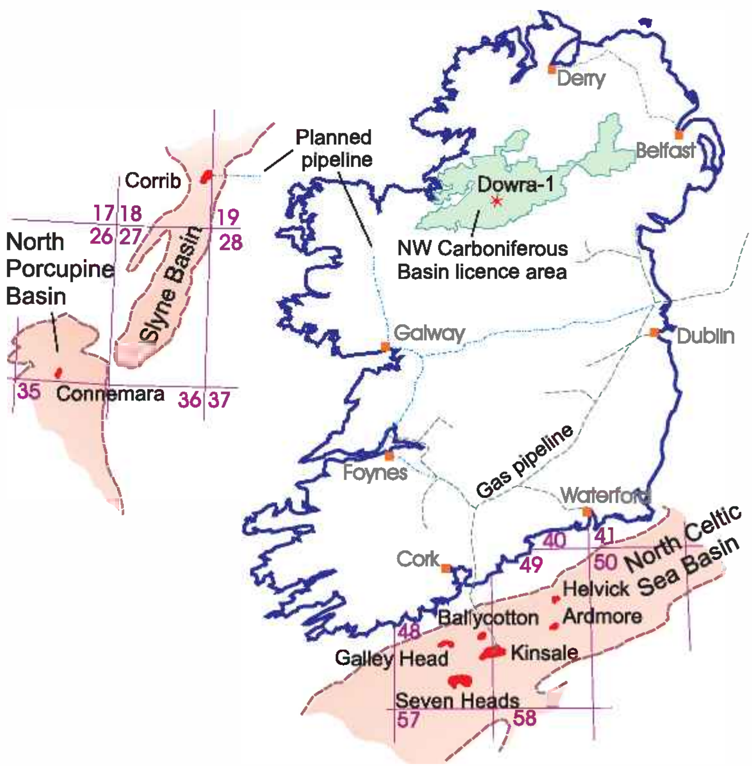


Figure 13.5 *Oil and Gas fields & offshore basins*

The Helvick discovery was made in the North Celtic Sea Basin in 1995, but had insufficient oil and gas reserves in Jurassic sandstones for development. In 1996, the first significant offshore find since Kinsale was made with the Corrib field in the Slyne Trough, about 70 km off the coast of County Mayo (Figs. 13.5 and 13.6). Containing about 850 billion cubic feet of gas in Triassic beds and with an estimated field life of 15 - 20 years, planning permission for an onshore processing terminal at Bellanaboy Bridge in County Mayo was refused in early 2003. It was planned that gas production, originally scheduled for late 2005, would be piped underground from the terminal into the Dublin gas grid, to be sold to domestic and commercial users. Subject to new development plans, Corrib gas production will compensate for the decline in the Kinsale fields and will help economic development in the west of Ireland with this indigenous gas supply.

No new frontier licences were issued during 2000, reflecting low oil prices, restructuring of the industry (company mergers resulting in fewer players) and a reluctance to commit to high-risk exploration in Irish waters.

Most prospective offshore basins are only starting to be explored. In much deeper waters, on the northwestern continental shelf, there are promising traps in the fault-bounded basins of Rockall and Hatton (Fig. 12.4), which contain up to 5 km of sediment. Economic viability is difficult when expensive deep-water technology is required for oil or gas extraction. However, drilling of the Dooish prospect in Rockall Basin during the summer of 2003, yielded significant hydrocarbon and will be further appraised. In nearly 1500 m of water, this is the second deepest well drilled in Irish water, and it has opened up great exploration potential in a frontier area.

13.3.1 KINSALE FIELD AREA

The Kinsale Head Gas Field was discovered by Marathon in 1971, 50 km southeast of the Old Head of Kinsale, within the ENE trending North Celtic Sea Basin (Fig. 13.5). Most of the gas reservoirs are at relatively shallow depths of no more than 1070 m, in Lower Cretaceous continental sands in a sand-shale cyclic sequence in which the shales form seals to the reservoirs. The oil was probably sourced from underlying Upper Jurassic shales and the trapping mechanism is mainly stratigraphical, due to enclosing shales and an overlying unconformity (Study Box 13.1). This major unconformity between Upper Cretaceous chalk and folded Lower Cretaceous and older rocks is recognised throughout Northwest Europe, and marks an important phase of folding, uplift and erosion following Lower Cretaceous deposition.

Kinsale, with its original gas reserves of 1.7 trillion cubic feet of gas, came on stream in 1978 but is due to cease production during 2003 - 2004. The small satellite fields of Ballycotton and Southwest Kinsale are also near to depletion. More than 1.5 trillion cubic feet of gas was produced from the area up to mid-2000.

The Seven Heads field to the southwest of Kinsale, was discovered in the 1970s, and its recent development, along with that of the Galley Head field, has been due to the availability of the Kinsale field infrastructure. The first gas is scheduled for the end of 2003, and it is expected to supply 10 - 15 % of Ireland's rapidly expanding domestic gas requirements for the next 15 years. Seven Heads also contains deeper oil reservoirs, and if developed, this would be the first commercial oil production from the Celtic Sea Basin.

Figure 13.6 *Oil rig, Corrib field*

13.3.2 ONSHORE IRELAND - THE NORTH WEST CARBONIFEROUS BASIN

There has been no commercial production from an onshore hydrocarbon reservoir to date. In the 1960s, the Dowra well (Fig. 13.5), drilled in Co. Cavan flowed a minor amount of gas from a Carboniferous sandstone at a depth of around 1240 m. This was one of multiple reservoirs in a deltaic sequence of tightly cemented calcareous sandstones sealed by overlying shales. They lie within a northeast - southwest trending basin in the Sligo - Leitrim area that forms part of the North West Carboniferous Basin stretching across the northern part of Ireland. This 'tight' gas sand, so called because there is little permeability within the rock, covers more than one million acres and has estimated recoverable gas reserves of up to 5 trillion cubic feet. Since 2001, an American exploration company specialising in unconventional natural gas properties has been drilling the various sands with a view to development.

13.3.3 THE IRISH GAS MARKET

Ireland's first offshore gas storage service, utilizing the South West Lobe of the Kinsale Gas field, began in 2001, enabling gas to be stored in summer months and delivered to the Irish market during the higher demands of winter. Gas for underground storage is first collected from surrounding fields by undersea pipelines, before being pumped down into the porous rock. When needed, the gas is pumped up through gas storage wells and piped to onshore facilities east of Cork City, where it is used for electricity generation, and is fed into the Bord Gais Eireann grid for national distribution (Fig. 13.5). The gas was also utilised in the manufacture of nitrogen-based fertiliser in the IFI (Irish Fertiliser Industries) plant at Marino Point until late 2002.

Indigenous gas accounts for only about 20% of the Irish energy market and the country currently imports more than 50% of its gas supplies from the U.K. However, natural gas is now the preferred fuel, and with plans for several gas-fired power generation plants, the present annual demand of 350 mcfd (million cubic feet per day) is forecast to rise to 480 mcfd by 2005. Any new source of indigenous gas, especially in the light of Kinsale's decline, will help to increase the country's diversity and security of supply.

13.3.4 REGIONAL DISTRIBUTION OF PETROLEUM AND GIANT FIELDS

Oil and gas deposits are found throughout the geological column, from the Cambrian (for example, Hassi Messaoud field in Algeria) to the Tertiary (for example, the giant Minas field, Indonesia). In Ireland, hydrocarbon is found offshore in the Triassic (Corrib gas field), Jurassic (Helvick, Connemara oil fields) and Lower Cretaceous (Kinsale gas fields) and there are potential deposits in deltaic Carboniferous sands onshore in the Northwest Basin.

The ideal geological setting for the location of a 'Giant Field', which is defined as one containing 500 million barrels of ultimately recoverable oil (or equivalent in gas), is in a basin within continental crust that has been associated with plate collision. This may be due to the greater thickness of limestones and sandstones found in such areas, or to organic productivity or burial conditions. The discovery rate for giant fields has declined sharply since the late 1960s, due to mainly economic factors, as there are numerous basins yet to be explored. Giants account for at least 65% of the world's proven reserves. The nearest giant field to Ireland is the Brent field (in Jurassic carbonates) in the North Sea, which was ranked 92nd out of the 509 known giants in the mid- 1980s. The largest giant field, Ghawer in Saudi Arabia, was estimated to contain around 88,000 million barrels equivalent of recoverable oil and gas. By 2001, about 880 giants had been discovered, of which 592 are concentrated in twenty 'clusters' around the world.

13.3.5 OPEC AND THE PRICE OF OIL

The Organisation of Petroleum Exporting Countries (OPEC) was founded in Iraq in 1960 to unify its country members' petroleum policies and, later, to set crude oil prices for its customers and production quotas from its members. The current eleven OPEC members, of which Saudi Arabia, Iran and Venezuela are the largest producers, are estimated to account for around 40% of the world's oil production.

The international trade in oil provides the physical base for the world's largest commodity market, but oil prices often behave unexpectedly due to the market's interaction with physical operational constraints, and economic and political forces.

Major world crude oils important for oil pricing are called "benchmark" crudes and are traded on international exchanges. Outside of the United States and Asian markets, North Sea Brent crude is used as a marker for much of the rest of the world's traded oil.

When oil prices rise (over ~$30 a barrel is high; less than ~$20 is low), as they did during 2003 because of the threat of war with Iraq (more than 60% of the world's proven oil deposits are located in the Persian Gulf region), OPEC tries to stabilise them by increasing production quotas from its member countries (especially Saudi Arabia as it can usually produce more than its agreed quota) so that the market is flooded with oil and the price subsequently falls.

However, the continuing post-'Iraq War' crisis and the failure to restore Iraq's oil exports quickly to world markets, has kept the price of Brent crude near to $30 a barrel. Such increases in energy costs have a detrimental effect on Irish and world economic growth, pushing up inflation rates.

Study Box 13.1 Origin, Migration & Trapping of Oil and Gas

Most oil and gas originates from the anaerobic decay of sedimentary organic matter (algae, plankton and plant material) in mainly marine, but also in lacustrine or fluvial environments. In a subsiding sedimentary basin, decomposing organic material is transformed into insoluble matter called kerogen through progressive burial and compaction. Kerogen will only mature into hydrocarbon if the right conditions of pressure, heat and, especially time, are applied. Slowly subsiding basins act as very large physico-chemical reactors, in which sedimentary organic matter in anoxic conditions is gently 'cooked' (at less than 200°C) over millions of years. Temperature is known to increases with depth due to the heat produced by radioactive elements in the earth's crust, and this geothermal gradient averages 25-30°C per km in depth. There are specific temperature ranges within which the generation, or expulsion, of hydrocarbons from the source rock will occur. The oil window averages between 60-130°C and the gas window between 130-220°C. This normally corresponds to depths of between 2-8 km.

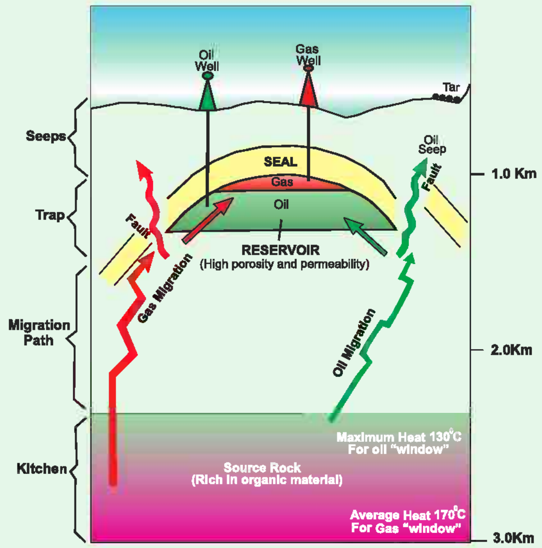


***Figure 1.** How an oil trap forms*

Different types of kerogen source differing types and amounts of hydrocarbon, the commonest and richest source of oil originating in black shales. The quality of the source rock is measured by its percentage of TOC (Total Organic Carbon), which ranges between 3-12 %. As hydrocarbons are less dense than surrounding rocks, they migrate upwards via bedding planes, joints and faults. They either escape as surface seeps, or accumulate in a coarse-grained host-rock, the reservoir, from which further migration is prevented by some type of impermeable rock barrier, known as the cap rock or seal.

A reservoir is a rock formation that can accommodate hydrocarbons in the voids (mainly pore spaces between grains, or joints) within the rock. Porosity is a measure of this storage space (30% is good), and permeability is gauged by the ease with which hydrocarbons can flow through it. The accumulation can only be extracted from the reservoir rock through this connectivity of pores or joints. The best reservoir rocks are coarse-grained sandstones and limestones

.

The association of reservoir rock and barrier is called a trap. Traps are formed by a structural or a stratigraphic arrangement of the rocks, or quite often, by a combination of both. A structural trap may be formed by a simple fold (anticline) in the rock layers, or by a fault bringing an impermeable layer such as shale against the reservoir rock, thereby sealing it. A stratigraphic trap can be produced by a sand body (e.g.deltaic) or carbonate reef enclosed by shales or by an unconformity juxtaposing an impermeable layer against a porous reservoir layer. Salt domes, by pushing up against adjacent impermeable layers, create the most effective traps but are relatively uncommon (see Study Box 11.1).

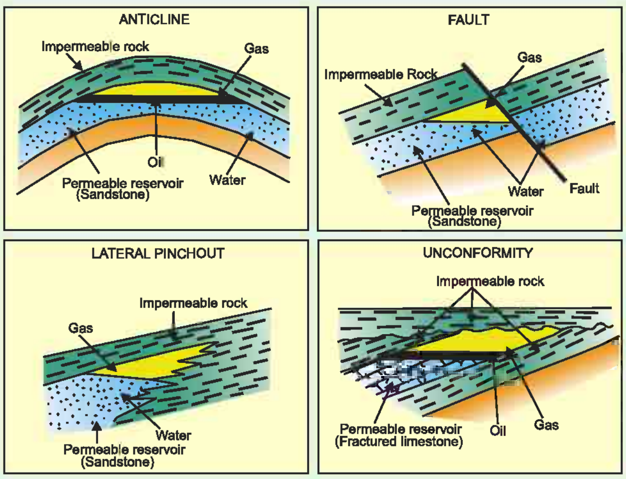


***Figure 2.** Types of oil traps*

Early oil and gas exploration was based on the location of oil seeps. Famous oil and gas seeps occur along the Californian coast indicating the presence of large adjacent inland fields, and hand-dug holes to collect oil from seeps at Baku, by the Caspian sea, were in use by 1594, making this the first true hydrocarbon field. Modern technology enables the identification of potential traps by the use of geophysical surveying, which provides a cross-sectional image of sub-surface rock layers by bouncing shock waves against them. If subsequent drilling successfully taps a reservoir, the hydrocarbon usually flows up into the drill pipe by pressure from underlying water that has separated out during migration. When this natural pressure subsides, the oil is extracted by other methods such as pumping.

14 EARLY TERTIARY - FLOOD BASALTS AND VOLCANIC CENTRES

14.1 THE PLATE TECTONIC SETTING IN THE EARLY TERTIARY

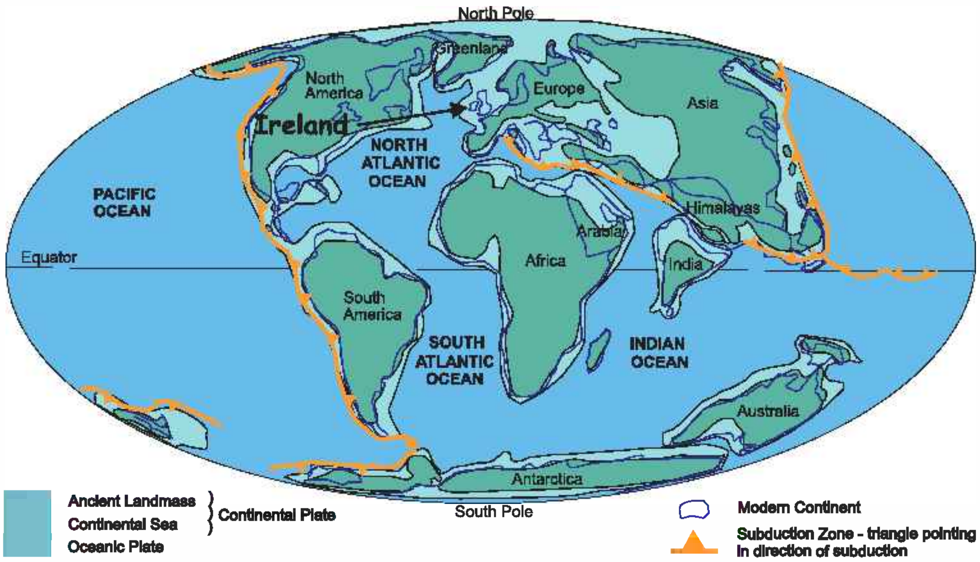


Figure 14.1 *Plate reconstruction for the early Tertiary*

By the beginning of the Tertiary Period, 65 million years ago, Ireland lay at about the latitude of present-day southern France and northern Spain (Fig. 14.1). Late Cretaceous and early Tertiary plate movements caused widespread emergence of northern land areas from the Cretaceous chalk sea. Uplift resulted in erosion of the low-lying land ridges that had formed islands in the Cretaceous seascape. Deep solution hollows were formed, in which a residual soil known as 'clay with flints' weathered out from the chalk and was able to support vegetation.

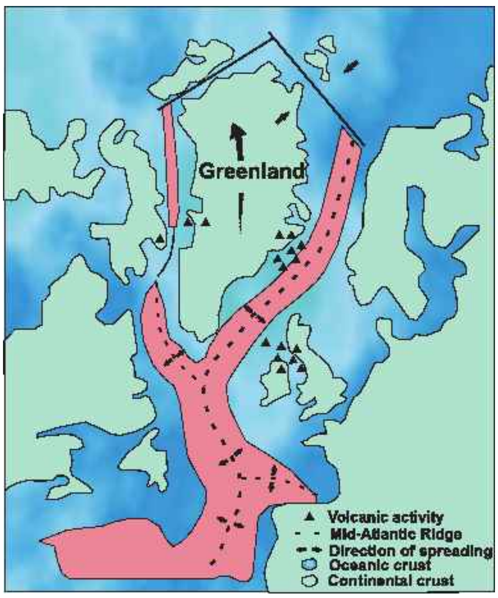


Figure 14.2 *The opening of the Atlantic and igneous activity*

The combined effects of crustal stretching (which preceded North Atlantic rifting) and a localised 'hot spot' within the Earth's mantle (section 1.2.2.4) created great volumes of magma that intruded and erupted (Fig. 14.2) to form the North Atlantic Igneous Province (Study Box 14.1). In Ireland the main phase of volcanism was between 62 - 58 million years ago.

14.2 VOLCANISM - VENTS, DYKES & PLATEAU LAVAS

Locally in northeast Ireland, volcanism began with explosive eruptions that resulted in thick deposits of ash. At Carrick-a-rede, on the Antrim coast, a thick sandy-coloured ash deposit containing dark blocks of basalt can be seen to cut vertically through the chalk, showing that it filled the vent of one of these volcanoes. This was followed by the intrusion of a swarm of parallel dykes along northwest - southeast fractures between 61 –58 million years ago, that stretched from the Rockall Basin, through Donegal and northeast Ireland, intensifying around Slieve Gullion, before extending into the English Midlands (Fig. 14.3).

In the northeast extensive basalt flows issued from the northwest - southeast trending fractures creating great lava fields across northeastern Ireland and the Inner Hebrides, and extending northwards to the Faroe Islands. In the Antrim area, repeated basalt flows filled hollows and buried the Cretaceous landscape, building up an extensive plateau (the 'Lower Basalts').

Similar explosive and fissure eruptions can be seen today in Iceland, where they have also been initiated by crustal thinning and extension associated with mid-Atlantic rifting.

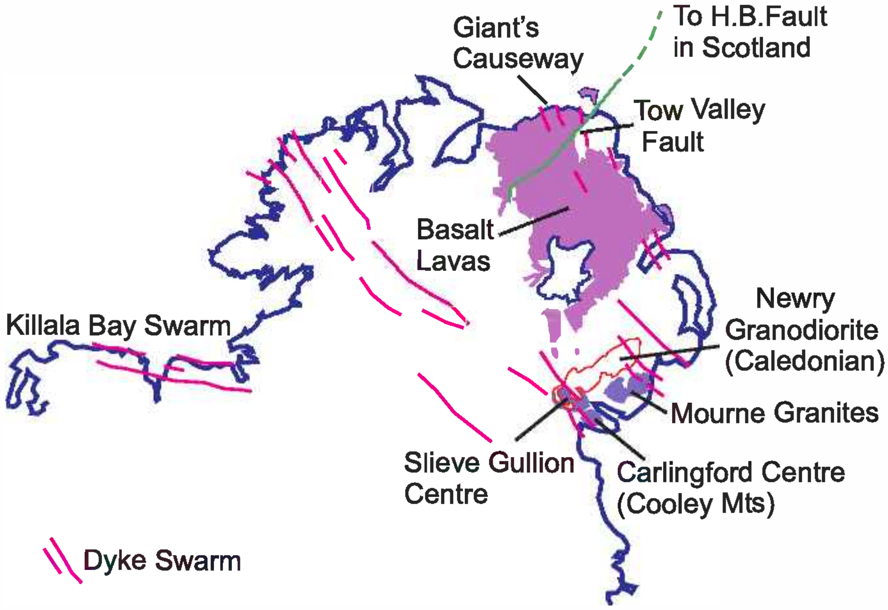


Figure 14.3 *Location of Tertiary igneous rocks in northeast Ireland*

14.2.1 THE LOWER BASALTS (LAVA FLOWS)

The Lower Basalts are made up of many individual overlapping flows of olivine-basalt up to 10 m in thickness. As the lavas erupted onto the surface, internal gas bubbles were released upwards and became trapped against the hardening upper surface or crust. These bubbles, or vesicles, were sometimes filled at a later stage with white minerals called zeolites that crystallised from hot circulating groundwaters. Good examples of these can be seen near Windy Gap at the Giant's Causeway. Pauses between eruptions may have spanned thousands of years as weathering of the upper surfaces produced thin reddish soils (the colour due to alteration of iron minerals in the basalt), in which patches of vegetation took hold. Overall the Lower Basalt phase probably lasted for 100,000 years, towards the end of which eruptions were less frequent and periods of erosion longer.

14.2.2 TROPICAL WEATHERING

The ensuing dormant period was characterised by a hot wet climate, during which deep weathering (including spheroidal weathering; see Fig. 14.4) of the Lower Basalt produced a red soil layer of laterite which is 15 m thick in places (see Chapter 15 & Fig. 15.1). These soils can be seen forming today in tropical regions such as central Africa.

Lignite, which is a type of low-grade coal, formed from decaying plant material in the laterite, and in some areas, such as near Portrush, was thick enough to mine (see section 15.2). This

Figure 14.4 *Spheroidal weathering*

'interbasaltic' period probably lasted several thousand years, as there was time for river valleys to be deeply incised into the Lower Basalt plateau. Lakes also developed and both conifer and deciduous trees took root on the landscape.

14.2.3 BAUXITE & ALUMINIUM PRODUCTION

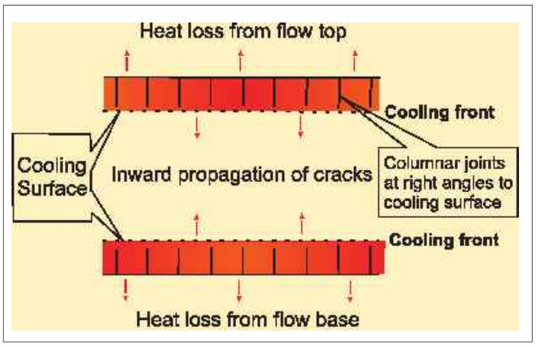
Rich in iron and aluminium from the chemical alteration of the lavas, the laterite was mined for bauxite (aluminium ore), in the Antrim area during the Second World War when supplies of aluminium were short for the aircraft industry. The last mine closed in 1945. Today bauxite is imported in bulk carriers from West Africa for refining into alumina at the Aughinish Alumina plant near Foynes, Co. Limerick. The Aughinish alumina plant is the largest in Europe and accounts for about half the shipping traffic on the Shannon. Alumina is then exported for further refining into aluminium in smelters around the world.

14.2.4 THE GIANT'S CAUSEWAY BASALTS

Following the weathering of the earliest basalts, a different type of basalt erupted across North Antrim and Rathlin Island. Vast thicknesses of tholeiite basalt, which is rich in silica, were poured out, resulting in the dramatic landscape now seen at the Giant's Causeway. These lavas were probably extruded as a result of intermittent movement along the Tow Valley Fault, a line of weakness south of the Causeway that extends northeastwards through Antrim to Scotland (Fig. 14.3).

The first flow was much thicker than any seen in the Lower Basalts, filling deep river valleys such as that forming the Giant's Causeway, where it ponded to a depth of 90 m. The spectacular basalt architecture here is due to a combination of this great flow thickness and the striking regularity of the famous columnar jointing, formed from cooling of the lava (Fig. 14.5). There are possibly as many as nine separate flows in the Causeway basalts, which become less impressive in thickness and jointing pattern towards the top.

Figure 14.5 *The Giant's Organ, Giant's Causeway*



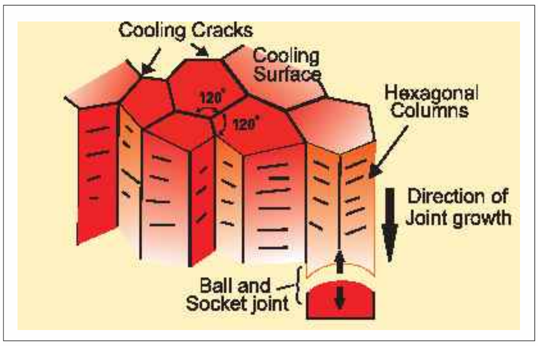


Figure 14.6 *Formation of polygonal columns*

Figure 14.7 *Hexagonal jointing, Giant's Causeway.*

The columns formed as a result of contraction during cooling of the lava (Fig. 14.6), the resulting polygonal pattern being similar to the cracked skin of mud left by a dried-out pond or lake. Basalt lava, with a temperature of about 1100ºC on eruption, rapidly loses heat along its upper and lower surfaces, which then contract, producing cracks radiating at 120º from each other. The cracks also propagate inwards as parallel sets of cooling joints at right angles to the cooling surfaces, as the lava continues to solidify internally. The surface cracks intersect each other, forming multiple-sided polygons of between three and seven sides, although they are most commonly hexagonal (Fig. 14.7). Shrinkage along the length of the incipient columns also produces convex-to-concave 'ball and socket' joints traversing the vertical columns.

14.2.5 THE UPPER BASALTS (LAVA FLOWS)

A second quiet period followed the cooling of the lavas, characterised by the development of another lateritic soil that can be seen capping the Causeway basalts. Renewed eruption of lavas from new fissures across the Antrim landscape formed the Upper Basalts. Like the olivine basalts of the Lower plateau, these are more extensive than, but do not match the volume and grandeur of the main Causeway tholeiite lavas. The Upper Basalt flows are thicker than those of the Lower Basalts but their original thickness is unknown as there has been substantial erosion of their upper part. A complete section with an overlying post-basaltic soil reveals 213m of Upper Basalts in a borehole from Lough Neagh. A volcanic plug in one of the small volcanic centres, through which these fissure eruptions were typically extruded, is preserved at Slemish near Ballymena.

Early Tertiary volcanic activity finally waned in northeastern Ireland as the underlying hot spot migrated elsewhere in the North Atlantic region.

Extensive quarrying of the basalt was carried out in north Antrim, mainly for road metal and concrete manufacture, but there are no known present-day operations.

14.3 THE VOLCANIC ROOTS OF SLIEVE GULLION, CARLINGFORD & THE MOURNE GRANITES

Following the extrusion of the north Antrim fissure lavas, further North Atlantic crustal stretching generated rising magma of a different composition, that erupted explosively and built up large volcanoes. Erosion of the volcanoes has progressively revealed their roots, which now form the mountains of Slieve Gullion with the surrounding Ring of Gullion, and the Cooley Mountains at Carlingford. This phase of magmatism appears to have migrated over time from Slieve Gullion to Carlingford (61 - 58 million years ago) before reaching the Mourne Centre between 55 - 52 million years ago (Fig. 14.3). The Mourne Mountains mark the site of the last pulse of magma, that evidently did not break the surface as a volcanic eruption, but cooled underground, as it has crystallised as an intrusive igneous rock.

14.3.1 SLIEVE GULLION - A VOLCANIC CRATER & RING DYKE

Slieve Gullion is encircled by a 'ring-fault', movement along which 58 million years ago, caused dramatic collapse (cauldron subsidence - see Chapter 6) of the original volcano, forming

Figure 14.8 *The Caldera de las Canadas, El Teide, Tenerife which formed when the Canadas volcano collapsed 0.17 million years ago.*

a caldera. Magma rising along the ring-fault erupted explosively, also forcing out chunks of Newry granodiorite, which can now be seen in an agglomerate-filled vent at Mullaghbane Mountain. The ring-fault was later intruded by acid igneous rocks such as granophyre (a microgranite in which the small-scale intergrowth of minerals gives a 'hieroglyphic' texture), producing a ring-dyke that stands out as the hills of the Ring of Gullion.

Later rocks located inside the ring-dyke (Slieve Gullion Mountain), consist of dolerite sills and a layered sequence of granophyre and gabbro. The intrusive rocks of Slieve Gullion Mountain represent only the eroded roots of the volcano.

14.3.2 CARLINGFORD - VOLCANO ROOTS & SOME CONE-SHEETS

The Cooley Mountains, marking the Carlingford igneous centre, are also all that remain of the root of a huge volcano. Along the southern margin of the complex, Carboniferous rocks are covered by 100 m of basaltic lavas, the only testament to the original volcanic structure. The two main rocks found in the centre are again gabbro and granophyre, which all solidified at depth beneath the volcano.

The basic rocks (gabbros) were intruded first, as multi-layered injections and now form the rugged northeastern arc of hills, including Slieve Foye, standing at 589 m. The later acid granophyre, which may have been injected as a ring-dyke, forms the more rounded hills of west Cooley and the lower central ground.

A final injection of magma formed cone-sheets of dolerite, that can be seen to the north of Carlingford, intruded into vertical sandstones and mudstones of Silurian age that were 'up-ended' during Caledonian deformation.

14.3.3 THE MOURNE GRANITE INTRUSIONS

The Mourne Mountains are composed of granites intruded at a high level in the crust, but which never broke the surface as volcanic lavas. Remnants of the magma chamber roof are preserved in older country rocks that show a thin zone of metamorphism. There are two main igneous centres, each with more than one phase of granite intrusion. Three older granites form the eastern centre and two younger granites make up the western centre, each magma having solidified before injection of the next pulse.

The two highest peaks of Slieve Donard and Commedagh are eroded remnants of the oldest granite, and located between them the 'Castles of Commedagh' form dramatically weathered pillars in the second granite. The western Mournes, composed of the two younger granite bodies, form lower hills such as Rocky Mountain. The summit here clearly shows the contrast between the white-coloured youngest granite and its pink, slightly older neighbour.

14.4 DYKES & SILLS

Dyke and sill intrusion around Ireland accompanied each phase of volcanic activity (Fig. 14.3). The large dyke on which Carrickfergus Castle stands, and the east - west trending dyke swarm that can be traced for nearly 70 km from Killala Bay in County Sligo to County Mayo, were intruded 58 million years ago. The latter swarm includes the Killala Gabbro, a 400 m wide dyke in which the magma cooled slowly to produce a coarse-grained gabbro (Fig. 14.9). Typically, much thinner dykes cooled relatively quickly to produce the medium-grained dolerite.

Figure 14.9 *A thin Tertiary dyke intruded into the Killala Gabbro*

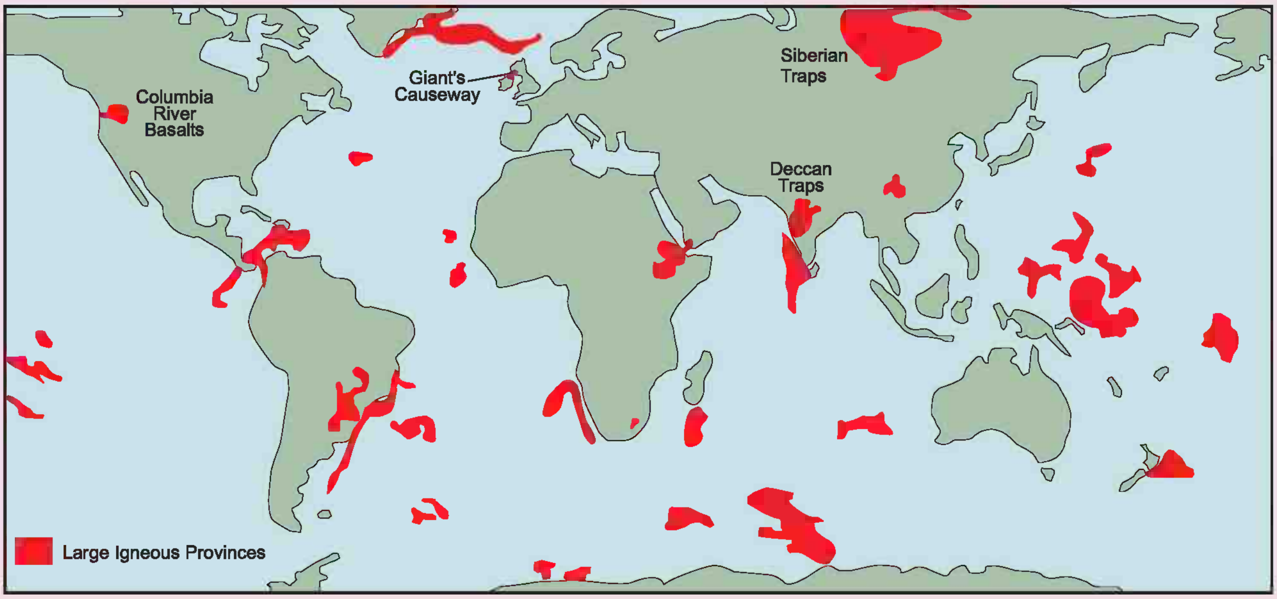
Evidence of Tertiary igneous activity is seen in rock types of various ages. The North Antrim Fair Head sill invades shales and sandstones of Carboniferous age, and cuts across younger Triassic sandstones and the Cretaceous chalk at Murlough Bay. Tertiary dolerite sills and dykes intrude Triassic sandstones in quarries near Newtownards, and the Portrush Sill on the North Antrim coast has been clearly squeezed between the bedding planes of ammonite-rich Jurassic clays. Tertiary dykes are found as far south as Firkeel Bay, Co. Cork, cutting Devonian sandstones.

Study Box 14.1 - Flood basalts

There have been events in Earth's history when huge volumes of basalt magma have been erupted, building extensive plateaux of lavas called flood basalts. Ireland's youngest volcanic activity was of this type. About 60 million years ago basalt magma engulfed the northern part of Ireland. The remnants of these flood basalts form the Antrim Plateau and include Ireland's best known geological site, the Giant's Causeway.

The Antrim Plateau is part of the North Atlantic Igneous Province, which also includes parts of the Inner Hebrides, the North Sea, the Faroe Islands, Iceland and eastern Greenland, fragmented since formation by the opening of the North Atlantic.

Similarly, flood basalts along the African continental margin of Namibia and the South American continental margin of Brazil were part of a single province (132 million years ago) before opening of the South Atlantic. Other well-known flood basalt provinces include the Deccan Traps of India (65 million years ago), the Siberian Traps (250 million years ago), which is probably the largest continental example at over 2 million cubic kilometres of basalt lavas, and the relatively small and young (16 million years ago) Columbia River Basalts of northwestern USA. There are many other occurrences of extensive basalt lavas on the ocean floors, and together the oceanic and continental occurrences are known as Large Igneous Provinces. Eruption of **Large Igneous Provinces** is very rapid in geological terms, approximately 1 million years for a whole province. Such rapid and voluminous eruptions are believed to be caused by hot plumes of mantle rock rising from great depth through the mantle and partially melting at shallow depth to produce huge volumes of basalt magma. The plumes that produce Large Igneous Provinces may be large-scale equivalents of the plumes that form hot spot volcanoes within tectonic plates, such as the Hawaiian chain.



The ages of some flood basalt provinces closely correspond to the timing of mass extinction events, leading to suggestions that the eruption of the large volumes of basalt could have been a cause of the extinctions. The Deccan Traps occur at the Cretaceous/Tertiary boundary, at the time of the mass extinction that wiped out the dinosaurs (Chapter 13). Although this extinction has been related to an asteroid impact, eruption of the basalts could have provided an additional contributary factor. The largest mass extinction event, at the end of the Permian (Chapter 11), was accompanied by eruption of the Siberian Traps. Addition of large amounts of SO_2 and CO_2 from the basalt magma into the atmosphere, and changes in ocean chemistry or circulation, are possible environmental impacts of Large Igneous Provinces that could be factors contributing to mass extinctions.

15 MIDDLE TERTIARY - LAKE CLAYS, LIGNITE, AND TECTONIC UPLIFT

15.1 CLIMATE & WEATHERING

Compared to the extensive lower Tertiary (Palaeocene) volcanic rocks in northeast Ireland, there are few places in Ireland where later Tertiary deposits still exist (Table 15.1). This contrasts with the south of England where extensive sedimentary rocks of Tertiary age underlie the London and Hampshire Basins. The only extensive sedimentary deposits in Ireland are the lake clays and lignites of Lough Neagh. These are of Oligocene age, that is, between 38 - 26 million years old. Well-documented examples of late Tertiary (Miocene and Pliocene) deposits in Ireland are very rare and comprise unconsolidated sediments found in karstic solution hollows in areas underlain by Carboniferous Limestone.

Modern day Ireland was land during the Tertiary Period and had been since the end of the Cretaceous. At the start of the Tertiary Period the land extended westwards out into what is now the Atlantic Ocean; north and westwards Ireland was connected to Great Britain. By the time that volcanic activity had ceased, the land areas had contracted eastwards so that the coast lay only a few kilometres west of the present Atlantic coast.

Period	Epoch	Age (beginning)	Tertiary Deposits in Ireland
	Holocene	10ka	
QUATERNARY	Pleistocene	2.3 Ma	
TERTIARY	Pliocene	7 Ma	Pollnahallia (Headford) lignite & silica sand karst fill
	Miocene	26 Ma	Hollymount solution pipe fill
	Oligocene	38 Ma	Lough Neagh Clays; Ballymacadam clays filling karstic pipe
	Eocene	54 Ma	(None known)
	Palaeocene	65 Ma	Inter basaltic beds e.g. Giant's Causeway

Table 15.1 *Tertiary sedimentary deposits in Ireland (Ma – millions of years; ka thousands of years).*

The climate at the beginning of the Tertiary was much warmer than today; it was warm temperate, as shown by plant fossils and spores. However, at the start of the Oligocene, the temperature cooled dramatically as ice-sheets started to cover Antarctica. The climate in Ireland was similar to that today, although perhaps a degree or two warmer.

From the start of the Tertiary Period, the rocks in Ireland underwent tropical weathering, with the result that most of the land was covered in a thick layer of residual aluminium rich clays. The interbasaltic horizon at the Giant's Causeway (Fig. 15.1) is a very good example of this. Here the older basalt weathered to form a soil rich in aluminium and iron. By mid-Tertiary times there were few places where fresh rock was exposed, except in Carboniferous limestone areas where limestone pinnacles might be seen (see Fig. 9.8). Much of the country probably resembled the badlands of North America, where poor soils covered the rocks which were only exposed in gullies and canyons carved out by streams which periodically carried the detritus away.

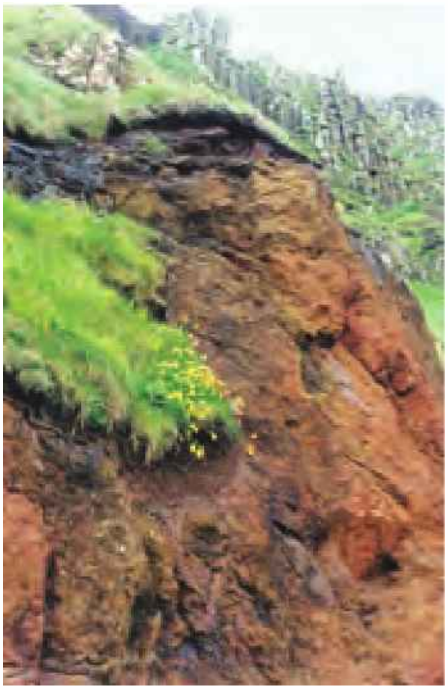


Figure 15.1 *Tropical weathering - the interbasaltic laterite horizon, Giant's Causeway, Co. Antrim*

15.2 LAKE CLAYS & LIGNITE

The formation of the clays found today around Lough Neagh, and also as far north as Ballymoney, were a result of this weathering, and tectonic downwarping that formed the Lough Neagh Basin. At that time the basin extended from Ballymoney, in the north, to Portadown in the south, a distance of about 70 km. Some 350 m of clays and lignites were deposited by rivers, which flowed into the lake about 35 million years ago. The lignite formed from vegetation that grew around and in the lake swamps, in a climate that was both warmer and wetter than today. Spores found in the lignite indicate that cypress, palms, and pine trees were abundant. They gradually rotted and were compressed to form the soft brown coal (lignite), which is interbedded with the clays and sands of the lake.

Lignite is a fuel of low calorific value and is also usually high in sulphur (though not the Lough Neagh lignite) and other pollutants. Consequently it can only be used profitably if it can be burnt near to source, for example in a power station. It has long been exploited in Germany, where in the former GDR vast strip mining operations fed power stations, and caused dreadful pollution (21.7% of world lignite production in 1994). Exploration for lignite around Lough Neagh has identified economic quantities of the fuel, but with the potential environmental problems related to increased carbon dioxide (CO_2) emissions and the need to reduce these under the Kyoto Agreement, the plan by an Australian company to strip mine the lignite for power generation is currently proving very controversial. It is possible to remove most of the pollutants before emitting the smoke, as is done in North Dakota, USA, but at a cost of 20 - 30% of the power station cost. Many people would prefer to use gas, which emits less CO_2, or use renewable forms of energy like the wind. One of the economic advantages of using an indigenous fossil fuel is the reduced dependence on imported fossil fuels, such as gas and coal, with the likelihood of more stable prices. It remains to be seen what decision is taken regarding the Lough Neagh lignites. There is often no simple answer.

It is possible that the Shannon and Erne Drainage Basins formed at the same time as Lough Neagh, due to tectonic downwarping. There is only a slight fall to the sea, which is a contributory factor in the annual flooding that takes place after heavy rainfall.

15.3 EROSION & CLAY WITH FLINTS

Over much of Ireland, the erosion of the landscape during the Tertiary Period resulted in the removal of the Cretaceous chalk. It has only been preserved in the northeast where it was protected by the cap of Tertiary basalt. Solution of the chalk to a lower level in England resulted in a concentration of insoluble residues known as 'clay with flints'. Similar residual deposits are found beneath the basalt in Ulster showing that solution started even before the start of Tertiary volcanism. The presence of abundant flint (siliceous nodules) in soils south of Cork City, suggests that chalk was eroded during the Tertiary Period in that area. Karstic attack resumed on the Carboniferous limestones once the chalk was removed over most of the country. Solution of

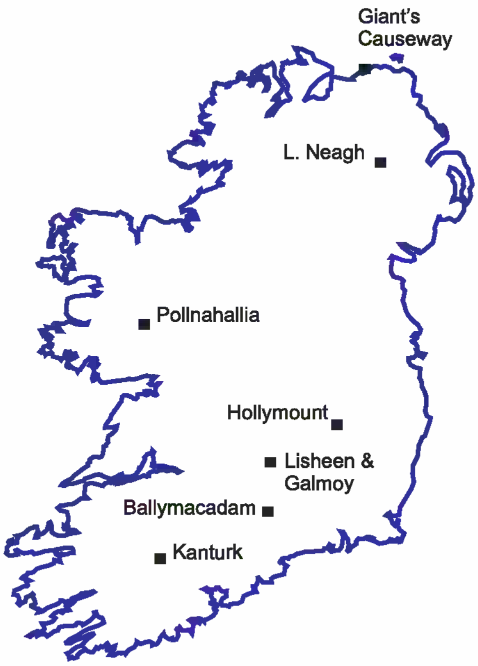


Figure 15.2 *Sketch map showing some of the principal Tertiary deposits*

the Carboniferous limestone can also leave a clay residue with nodules of chert (another form of silica similar to flint). Such cherty residues have sometimes been reported in mineral exploration boreholes. The protection afforded by this thin cover of clay and chert would eventually slow the rate of erosion of the limestone.

15.4 KARSTIC PIPES

In many places the Carboniferous limestone is penetrated by karstic pipes that contain sands, clays and lignites of Tertiary age (Table 15.1). One such pipe is located at Ballymacadam, Co. Tipperary where pollen similar to the Lough Neagh localities has been found (Fig. 15.2). Recently sediments containing a flora of Oligocene age have also been found in caves near Kanturk, Co. Cork. The sediments found in these karstic pipes may have originated from a depression similar to Lough Neagh, filled with lake sediments, but originally located at a higher level than the present land level.

Estimates of erosion of Carboniferous limestone in the Burren, where the limestones are directly in contact with the elements, suggest the removal of 0.053 mm per annum. If this rate is projected backwards it means that 53 m of limestone was removed in 1 million years, or more than 1000 m of limestone vanished in the last 25 million years. Returning to Ballymacadam, if such a high rate of erosion had applied here, it seems improbable that the Tertiary clays would have survived. Thus it seems likely that the Carboniferous limestone surface of the midlands is very old, and rapid erosion has resumed only where that cover of clay and woodland has been removed after the affects of the Ice Age.

Another karstic pipe filled with Tertiary sediments has been described from Hollymount, north of Carlow. The contents of the pipe are somewhat younger than the Lough Neagh and Ballymacadam clays. It has been dated as about 15 million years old. Plant evidence suggests a forest rich in trees growing in a climate a little warmer and less seasonal than today.

Study Box 15.1 Tertiary tectonics

The paucity of Tertiary rocks in Ireland has made an understanding of Tertiary geological events and processes difficult to fathom. Recent research, combining geomorphological work and sophisticated dating techniques, however, is demonstrating the importance of onshore earth movements at this time. The rate of Tertiary denudation can be estimated by measuring the decay of minute amounts of radioactive uranium to lead, contained in crystals of the calcium phosphate mineral apatite. The fission of the uranium atoms leaves minute tracks in the apatite crystal which are preserved when the temperature of the crystal falls below about 110°C. Measuring the length and number of these tracks can be used to estimate the time since the rock last cooled below the 110°C threshold.

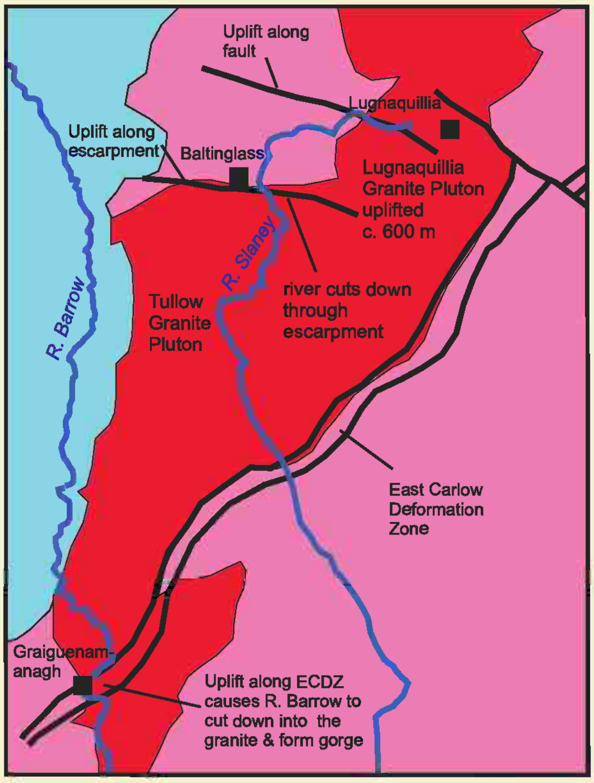


Figure 1. *Tertiary uplift in SE Leinster*

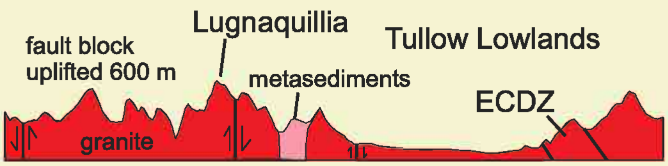


Figure 2. *Cross-section through Lugnaquillia area*

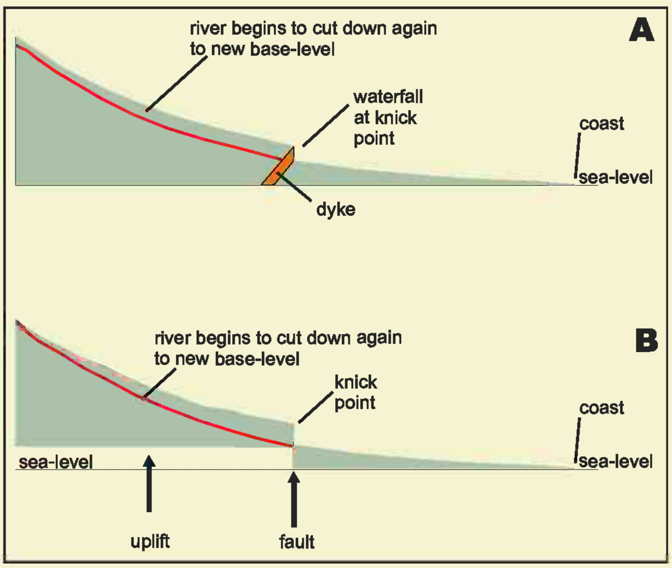


Figure 3. *The formation of a knick point due to (A) a dyke (B) fault uplift*

Work in Wicklow demonstrates that the granite of Lugnaquilla Mountain and of the Tullow lowlands to the south cooled below 110°C at the same time in the early Tertiary and yet there is a 600 m difference in elevation between the two granites. There is no other reason for the rate of denudation to have been different between the granites. An E-W fault has been interpreted adjacent to an escarpment along which uplift is postulated to account for the difference in elevation (Figs 1, 2).

The granite (Fig. 1) was also gradually uplifted during the Tertiary Period, relative to the limestones to the north and Ordovician rocks to the south along a fault shear zone, the East Carlow Deformation Zone. The erosive power of the R. Barrow cut down through the granite to form the 75 m high gorge at Graiguenamanagh, keeping pace with the tectonic
Uplift. The river is sinuous to the north and south of the gorge but cuts down with low sinuosity through the gorge.

Rivers will always attempt to erode from their higher upper reaches down to base-level, that is where a tributary joins the main river or the main river reaches sea-level.

Local base-level in the higher reaches of a river may be established due to encountering harder rock, a dyke (Fig. 3), or due to fault uplift. During the Tertiary Period knick points developed on many rivers due to uplift along faults cutting across the river. The rivers are now gradually eroding back the upper reaches to remove the knick point and re-establish base-level at sea-level.

16 QUATERNARY - THE ICE HOUSE

The Quaternary Period, the start of which is marked by the onset of cold conditions, officially covers the last 1.8 million years of geological time and is divided into the Pleistocene and Holocene (International definition based on evidence from Italy). However, in northwest Europe the first major cold period started some 2.3 million years ago. Although Quaternary deposits are not shown on the accompanying map, they are important to discuss because most of the rocks of older periods have been sculpted, to some extent, by the ice, which covered Ireland during the Pleistocene and in the lowlands, unconsolidated deposits left behind by the retreating glaciers and ice sheets mostly obscure the rocks. Also the processes and events, which are well described in the Pleistocene Ice Age, can to a more limited extent be recognised in earlier 'ice house' phases in the Precambrian (section 16.3), Ordovician and Carboniferous Periods (Figs 16.1 & 16.2). The Quaternary Period also includes the events and deposits laid down since the end of the last Ice Age about 10,000 years ago (the Holocene).

Figure 16.1 Precambrian Glaciation - Cleggan Boulder Bed

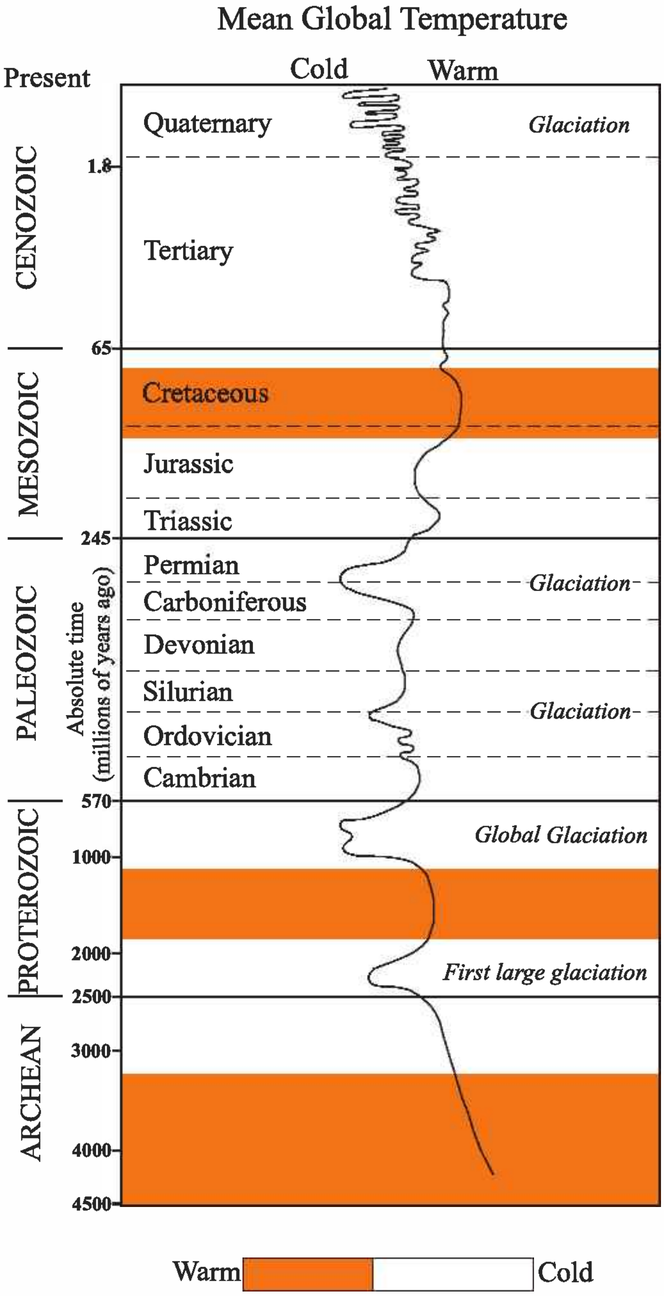


Figure 16.2 *Graph of global temperature changes through geological time.*

16.1 CLIMATE & THE ICE AGE

Temperatures began to fall during mid-Tertiary times (Fig. 16.2), accompanied by growth of the Antarctic ice sheets. Temperatures continued to fall as the Arctic ice sheets spread across most of northern Europe and North America, at the beginning of the Quaternary Period. Average global temperatures decreased from 22^{o}C at the start of the Tertiary to as little as 12^{o}C during the Pleistocene. As temperatures fell, some of the snow that had fallen in the winter remained throughout the summer and was compacted by the snowfalls of the next winter. In this way, over thousands of years ice sheets built up gradually. Where the ice was on a slope, it tended to move downslope under gravity and so glaciers formed. Glaciers usually picked out the easiest route by flowing down pre-existing valleys. Frost shattering of rock on mountains exposed above the glacier level produced scree which became incorporated in the ice of the glacier as it moved away from the heads of the valley (for example, Errigal in Co. Donegal). These rock fragments, incorporated in the ice, were an extremely erosive tool that ground away the underlying rock surface. Originally 'V' shaped valleys, carved by streams, were opened out to become 'U' shaped under the influence of glaciers. Several mountains including Errigal, Benbulbin (Fig. 16.3), and the Galty Mountains have been identified as probable nunataks, i.e. areas that protruded above the ice sheet.

Figure 16.3 *Benbulbin – a possible nunatak*

When temperatures gradually rose, the ice began to melt, and glaciers retreated, dumping ground up rock as moraines (till/boulder clay). Sub-glacial streams deposited elongate ridges of sand and gravel known as eskers (Fig. 16.4). Drumlins (Fig. 16.8) were deposited from the ice, probably when it slowed down or melted, resulting in it becoming overloaded with material.

Figure 16.4 *Split Hill Esker, north of Kilbeggan*

16.2 ICE ADVANCES & RETREATS

During the last 1.7 million years or so, there were perhaps as many as six periods of ice advance followed by ice retreat. During the inter-glacial periods the climate was as mild as today, or even 1 – 2° warmer and forests gradually spread across Ireland. The erosive power of the glaciations later destroyed most of the evidence of the older glaciations in Ireland. Today we can only identify evidence of the last two glaciations, which took place during the last 500,000 years. The older of the two glaciations is known as the Munsterian, because evidence only remains from the extreme southwest of the country. The younger glaciation is called the Midlandian and covered all but the southernmost part of Ireland (Table 16.1).

Stage	No. Of Years before present
Littletonian Warm Stage	0-10,000
Late Glacial	13,000-10,000
Midlandian (Drumlin) Cold Stage	35,000-13,000
Aghnadarraghian Mild Stage	65,000-35,000
Midlandian (Main) Cold Stage	79,000-65,000
Fenitian Mild Stage	122,000-100,000
Eemian Warm Stage	132,000-122,000
Munsterian Cold Stage	302,000-132,000?
Gortian Warm Stage	428,000-302,000?
Ballylinian Warm Stage	500,000-480,000

Table 16.1 *The various Glaciations and Interglacials.*

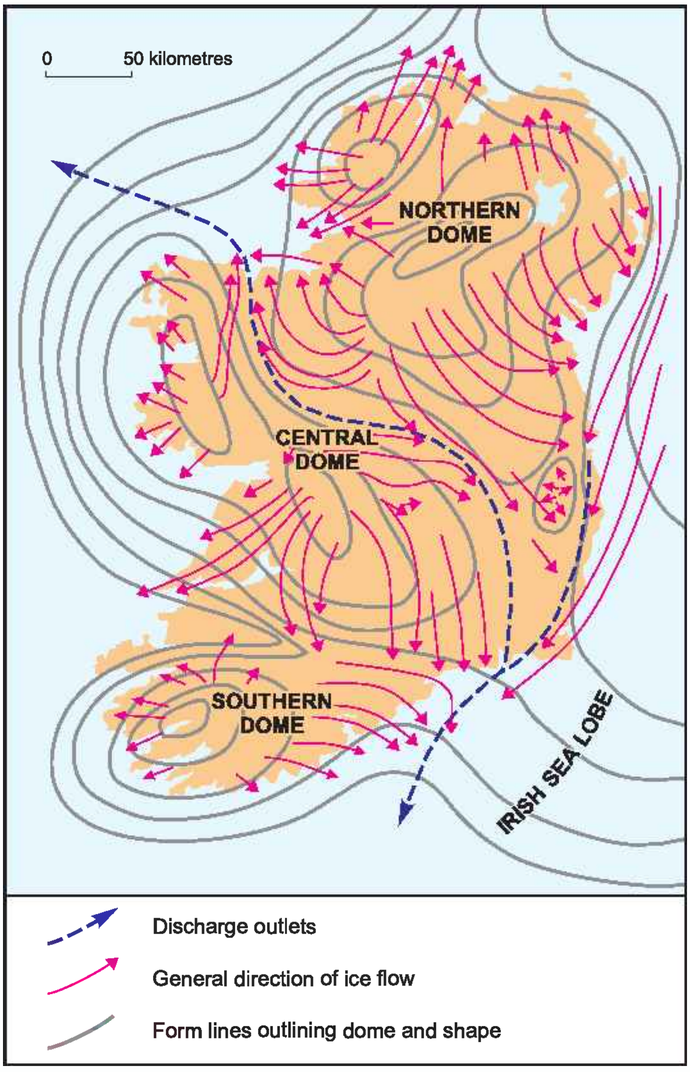


Figure 16.5 *The pattern of glaciation during the Midlandian Glaciation*

Physical evidence of the interglacials is difficult to find. The Gortian Warm Stage (428,000 – 302,000 years ago?), which preceded the Munsterian Glaciation, is represented by a peaty accumulation below a thick glacial deposit in a river valley at Gort, Co. Galway. Sandy clay containing pollen shows a development from cold loving plants and trees (for example, herbs and birch) to trees that grow in a warmer climate (for example, oak and pine). Deposits of Gortian age have now been recorded from about a dozen sites.

Evidence for the Eemian Warm stage (132,000 - 122,000 years ago), which followed the retreat of the Munsterian Glaciation, is difficult to identify in Ireland. There are a few tantalising deposits that may be younger. At Fenit, Co. Kerry, a cliff section shows periglacial deposits resting on peaty mud, below which are beach deposits raised above the modern beach, resting on a wave-cut platform. The mud is dated to between 115,000 - 120,000 years ago using radiometric dating techniques (the breakdown of uranium to thorium). Another beach deposit is recorded at Ballybunnion, Co. Kerry, where the shore platform is cut in till on which the raised beach rests. The beach is interpreted as Eemian in age and rests on till of the Munsterian Glaciation. A raised beach, typically 4 – 6 m above current sea-level, is found intermittently all the way round the coast from Co. Waterford, through Co. Cork to Co. Mayo. This, the Courtmacsherry Raised Beach (Fig. 16.6), after the locality in Co. Cork where it was described in the 19th century, may well have been deposited and the wave-cut platform cut when the sea-level was higher during the Eemian Warm Stage. Similar beach deposits are found in South Wales and contain fossil mollusc shells which have been dated as Eemian. Unfortunately no mollusc shells have been found in the Irish beach deposits. The age of this raised beach is still the subject of controversy but recent dating of the raised beach at Fethard, Co. Wexford, using a new technique of infra red stimulated luminescence is broadly consistent with the Fenit date.

Figure 16.6 *The Courtmacsherry raised beach*

Figure 16.7 *Glacial till from Lecanvey, Clew Bay*

The Midlandian ice sheets are now divided into two phases, divided by a relatively short warmer period when tundra conditions prevailed, known as the Aghnadarraghain Interstadial or Mild Period (Table 16.1). The main Midlandian cold stage ran from about 80,000 – 65,0000 years ago. The ice-sheets covered all but the highest parts of Ireland as far south as a line from the Shannon Estuary to north of the Wicklow Mountains and then down the Irish Sea coast to the Saltee Islands of Co. Wexford. A separate ice dome covered most of Kerry and West Cork. The Aghnadarraghian Mild Period is identified near Lough Neagh where till, of Midlandian age rests on Tertiary lignite. Above the till is gravel, which contains bones of woolly mammoth and sands with washed in vegetation where beetle remains are common. These sediments pass up to till, which is assigned to the late drumlin phase of the Midlandian Cold Stage. The later advance of the Midlandian took place between 35,000 - 13,000 years ago and most of the drumlins seen today, for example under Clew Bay (Fig. 16.8), in Monaghan, and in Bantry Bay, were deposited beneath the ice sheet at that time. Areas to the south of the ice sheet in Munster were a cold desert (tundra). With much of the ocean water locked up in ice sheets, global sea-level fell. At the maximum extent of glaciation, global sea-level was about 130m lower than today.

Figure 16.8 *Drumlins in Clew Bay*

16.3 SNOWBALL EARTH

There is growing evidence to show that in late Precambrian times there was a period of glaciation so severe that the entire Earth's surface was frozen solid like a snowball. The oceans are thought to have frozen to a depth of 1 km, but did not freeze to the bottom due to the heat coming from the interior of the Earth. The trigger that started the freeze is thought to be the break up of the supercontinent Rodinia (Fig. 2.1) that left small continents clustered in the tropics. Formerly land-locked areas were then closer to oceanic influence that resulted in increased rainfall. This removed more of the greenhouse gas carbon dioxide from the atmosphere resulting in a global fall in temperature. Large ice caps then formed in polar regions. The white ice reflected more heat back into the atmosphere so accelerating the growth of the ice sheets in an unstoppable way. Evidence for 'Snowball Earth' is found today, for example, in Namibia, where there are glacial till deposits which are known from palaeo-magnetic data to have formed in tropical latitudes in the late Precambrian. Similar glacial deposits of this age are found today on every continent. Lying immediately above the tillites in Namibia, however, are limestones that suggest an abrupt change in climate from glacial to tropical. So how did the climate change back from the big freeze? With the freeze, the cold dry air prevented the growth of land glaciers and lead to large deserts of windblown sand. Carbon dioxide emitted from volcanoes was not removed from the atmosphere by rain and so it gradually built up until it formed a blanket around the Earth allowing it to gradually warm up again. Eventually the sea-ice melted in the tropics and the moisture refroze in polar latitudes and fed the growth of land glaciers. The open sea in the tropics absorbed more heat from the sun resulting in a rapid rise in global temperature with intense greenhouse conditions. This rapid climatic change provided an ideal opportunity for the rapid evolution and radiation of new life forms as seen in the fossil record at this time.

16.4 THE HOLOCENE - POST GLACIAL

The start of the Holocene post-glacial phase of the Quaternary Period is called the Littletonian (Table 16.1) after Littleton, Co. Tipperary (in England the same time is called the Flandrian Interstadial).

Environmental and landscape changes in the Littletonian are dominated by eustatic sea-level changes and isostatic rebound after the melting of the ice sheets, climate change, and human activities.

With the retreat of the ice-sheets there was a global (eustatic) rise in sea-level, which started some 20,000 years BP. This can be seen best in southern Ireland where valleys carrying small rivers opening out to the sea in Cork and Kerry now form rias (drowned valleys) like Bantry Bay and the Bandon river (Fig. 16.9). However, in the north of Ireland, the effect of unloading of the ice-sheets has resulted in a net land rise of about 22 m in the last 16,000 years. The evidence for this can be seen in the raised beaches at Islandmageee and former sea stacks above high water mark at Cushendun and Ballintoy Head, Co. Antrim. This isostatic rebound was slower to take place than the eustatic rise as it takes longer for the viscous mantle material to readjust beneath the lithospheric crust. The net result of eustatic and isostatic readjustment, which is still taking place, is that Ireland (and Great Britain) is tilting to the south with the north rising. The other result of sea-level changes was the drowning of the tenuous landbridge between Northern Ireland and Scotland between 11,400 – 10,200 years before present (BP) (the landbridge between southern Ireland and southwest England was broken about 14,000 years BP).

Figure 16.9 *A drowned valley (Ria), Bandon River Valley, Co. Cork*

The record of sediments, fossils and landforms demonstrates climate change. Between 9000 – 6000 years BP, precipitation was lower and confined to winter months and the summers were a degree or so warmer on average than today. The lakes that are extant today were larger at the start of the Holocene and most of the country was gradually covered by forest. Plant and tree remains in the bogs are evidence of former forests. The native forest took hold between 7,500 – 5,000 years BP with elm, hazel, oak and alder successively colonising the landscape. Pollen found in small mountain lakes shows that many of the mountains were forested (for example, the Nephin Begs and Wicklow Mountains).

Peat now covers about 16% of the land area of Ireland. Acid peat is maintained by high rainfall. Sphagnum moss absorbs the water and helps to raise the local water table above the surrounding area.

The raised bogs, much of which have now been removed for fuel and horticultural purposes, started as post-glacial lakes. In the warmer summer climate referred to above, active algal precipitations raised the PH of the lake water causing dissolved limestone ($CaCO_3$) to sediment as marl. At the lakeshore, pine, willow and reeds grew and the detritus from decaying vegetable matter gradually encroached over the lake margins and over the marl to form fen peat, which eventually filled the lake basin. As the climate became more oceanic so sphagnum moss grew over the fen peat to form the acid raised bogs.

Blanket bogs form the majority of surviving boglands today and are widespread. Many blanket bogs reveal tree stumps at their base showing that the land was originally forested. Some also reveal evidence of human settlement and field systems beneath the bog. The formation of these bogs may have been partly a consequence of human activity. The focus for the development of the blanket peat was small lakes where peat could develop in waterlogged depressions. With deforestation, burning and grazing, run-off increased, providing ideal conditions for peat growth in the more oceanic climate. The present character of the landscape was created largely in the Bronze Age about 4,000 years BP.

Study Box 16.1 The causes of glaciations

There are many factors and theories current and no general consensus as to the cause of glaciations. Some of the more important factors identified as possible causes are summarised below.

1. Polar ice sheets are more likely to form when continents, due to plate tectonic movements cover the polar regions or cluster in high latitudes, as continents reflect back heat into the atmosphere while oceans act as heat sinks.
2. Interplanetary dust entering the atmosphere at such times may act as nuclei for ice crystals to grow on, resulting in less solar radiation reaching the ground and so leading to further cooling.
3. As more and more ice forms rather than rainfall returning to the oceans, so global sea-level falls, exposing more continental shelf, further accentuating the onset of glaciation.

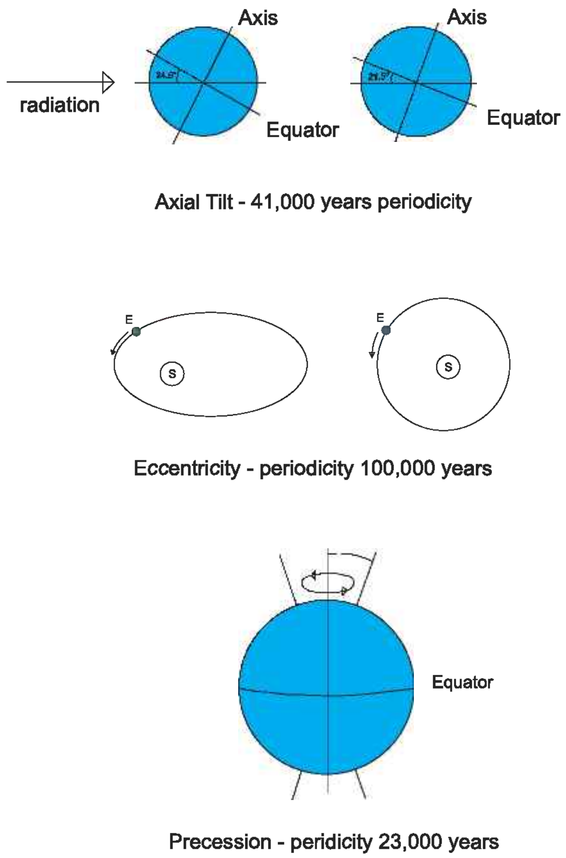


Figure 1. *Milankovitch cycles*

Milankovitch Cycles
The input of solar radiation (insolation) is affected by the Earth's axial tilt, eccentricity, and precession (wobble about its polar axis) (Fig.1). These factors may influence the potential for growth or decay of polar ice sheets in favourable circumstances. However, the drop in insolation due to the 100,000 year eccentricity cycle proposed by Milankovitch is thought to be inadequate to start ice-house conditions.

Orbital inclination - the Earth and the other planets revolve around the sun in a flat plane. Not all the planets are in exactly the same plane but the Earth's orbit varies up and down from the average of the Solar System's plane, which is close to that of Jupiter's (Fig. 2). This change in orbital inclination varies on a roughly 100,000 year cycle, which matches global temperature data collected from ice cores. Astronomers **Muller and Macdonald** speculate that an interplanetary and meteoroid dust belt is intersected every 100,000 years due to this change in the Earth's orbit which has a cooling affect (Fig. 2).

Astronomers **Hoyle & Wickramasinghe** further suggest that comets impact the oceans about every 100,000 years and the addition of vast quantities of water into the atmosphere, due to the impact, results in green house warming and thus leads to the warm interglacial periods.

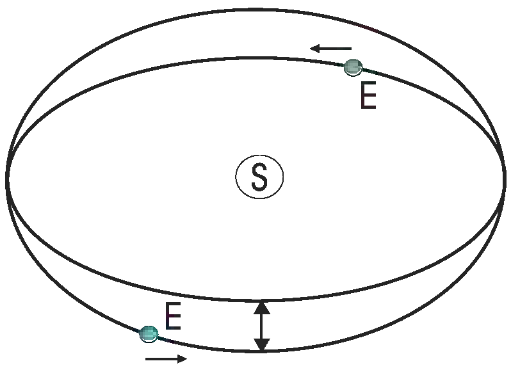


Figure 2. *Orbital inclination cycle - c. 100,000 years*

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MAGAZINES OF GENERAL INTEREST

Earth Science 2000 (ES2k) – popular glossy free magazine - Raising awareness of Earth Science in Ireland – Editor – Tony Bazley, ES2k, 24, Ballymacreely Road, Killinchy, Newtownards, Co. Down BT23 6RP Te; 028-9754-2396, email: tonybazley@csma-netlink.co.uk

Science Spin – Ireland's Science and Technology Magazine – Editor - Tom Kennedy – Duke Kennedy Sweetman Ltd, Foxford Woollen Mills, Foxford, Co. Mayo, Tel: 094-9257801

Down to Earth – popular free Earth Science newspaper published in UK – Editor, Chris Darmon, Geosupplies Ltd., 49, Station Road, Chapeltown, Sheffield S35 2XE, UK, Tel: 0114-245-5746.

Geology Today – popular glossy magazine published bimonthly by Blackwell Publishing Ltd – discounted subscription for members of Irish Geological Association – Editor, Peter Doyle, Geology Today, Burlington House, Piccadilly, London WIV 9AG, Tel:0044-20-7434-9944.

RECOMMENDED WEBSITES

BBC Education The essential Guide to rocks http://www.bbc.co.uk/education/rocks/rocky.shtml

British Geological Survey (Education pages, Magazines etc.) http://www.bgs.ac.uk/

Cork Geological Association (field trips and lectures for amateurs) http://www.corkgeology.homestead.com/cga.html

Dept. of Geology University College Cork (Evening Diploma course in Geology) http://www.ucc.ie/ucc/depts/geology/courses/diploma/diploma.html

Earth Science 2000 (ES2k) (News & events etc.) http://www.habitas.org.uk/es2k/

Earth Science Teacher's Association (Resources, links etc.) http://www.airburst.co.uk/esta/index.htm

Geological Museum – Trinity College Dublin http://www.tcd.ie/Geology/MAIN-PAGE/museum.html

Geological Survey of Ireland (Geology for everyone, events & activities, GSI shop – maps pamphlets etc.) http://www.gsi.ie/

Geological Survey of Northern Ireland http://www.bgs.ac.uk/gsni/home.html

Irish Geological Association (Newsletters, Lectures, excursions) http://www.ucd.ie/geology/IGA/

Palaeomap Project (Plate tectonic animations etc.) http://www.scotese.com

Science Spin (Ireland's first science magazine) http://www.sciencespin.com/

The Geological Society (Teaching resources etc.) http://www.geolsoc.org.uk/

The Institute of Geologists in Ireland (Useful links to other geological sites) http://www.igi.ie/

Ulster Museum (Exhibitions, Lectures etc.) http://www.ulstermuseum.org.uk/

United States Geological Survey (USGS) (Education pages etc.) http://www.usgs.gov/

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FIGURES

Figure 2.2 - G.I. Alsop; Figure 3.6b - modified after Crimes *et al.* fig.6, *Geol.* J. 30, 89-109; Figure 13.4 - Stephen Barnes, Karst Working Group, 2000, Geological Survey of Ireland; Figure 9.12 – after E. Doyle *et al.*, *Directory of Active Quarries and Pits in Ireland*. Geological Survey of Ireland; Figure 1.4, 1.23, 1.31 – modified after D. Edwards & C. King, 1999, *Geoscience. Understanding Geological Processes,* Hodder and Stoughton 256pp.; Figure 9.9 - Tim & Pat Fogg; Figure 14.3, 14.7 – Sarah Gatley; Figure 9.6 - based on 1:500,000 Geological Map in prep., Geological Survey of Ireland; Figure 14.2 – modified after Harland, 1969. Contribution of Spitsbergen to understanding of the tectonic evolution of the North Atlantic region, pp 817-851 *in* North Atlantic: Geology and Continental drift. *AAPG Memoir* 12; Figure 16.2 – after Hart (ed), Climates past and present, *Geol. Soc. Lond. Spec. Pub.* 181, fig.1; Figure 9.14 – Irish Association for Economic Geology; Figure 1.3 – after W.J. Kious & R.I. Tilling 1996, *This Dynamic Earth*, USGS; Figures 6.2, 6.3, 13.6 & 16.1 – Barry Long; Figure 1.4 - based on P & S waves, Lutgens, F.K. & Tarbuck, E.J. *Essentials of Geology*. Merrill Publishing Co. Ohio, 3rd ed. 378pp.; Figure 14.6 – modified after Lyle P. A., *Geological Excursion Guide to The Causeway Coast*. Environment and Heritage Service, 90 pp.; Figure 10.6 - modified after Matte P. 1991. Concretionary history and crustal history of the Variscan fold belt in Western Europe, *Tectonophysics,* 196, 309-337; Figures 9.3, 9.7, 15.1, 16.7 - Conor MacDermot; Figures 1.7-1.13, 1.15, 1.17-1.20, 1.26, 2.3, 3.2, 3.4, 4.2- 4.7, 5.2, 5.3, 6.5, 6.7 – Brian McConnell; Figure 12.4 - modified after Naylor, 2001 fig18.1 *in* Holland 2001; Figures 3.5, 3.6a, 7.9, 9.2, 9.8, 16.8 - Matthew Parkes; Figure 16.4 - Xavier Pellicer; Figure 6.6 - modified after Pitcher W.S. and Berger A.R., fig. 16-2 1972. *The Geology of Donegal: a study of granite emplacement and unroofing,* Wiley. pp435; Figure 1.14, 1.16, 1.21, 1.24, 1.25, 7.3, 7.6, 7.7, 14.4, 14.5, 14.9, 16.3 – Markus Pracht; Figures 2.1, 3.1, 4.1, 5.1, 7.1, 8.1, 10.5, 11.1, 12.1, 13.1, 14.1 - modified after Scotese, C. R., 2001. *Atlas of Earth History, Volume 1, Paleogeography*, PALEOMAP Project, Arlington, Texas, 52 pp.; Figures 8.2, 9.1a,b, 10.2, - based on Sevastopulo 2001 *in* Holland (ed) 2001 ch.10; Figure 11.3, 12.3 – Mike Simms, Ulster Museum; Figures 1.1, 1.2, 1.6, 1.31-1.35, 7.5, 7.8, 8.3, 9.4, 9.5, 9.10, 9.11, 10.1, 10.4, 10.7-10.9, 10.10, 11.4, 11.5, 14.8, 15.2, 16.6, 16.9 – Andrew Sleeman; Figure 2.4 – Siobhan Sleeman; Figure 11.2 – based on Smith, D.B. & Taylor, J.C.M. 1992. Permian. *in*: *Atlas of Palaeogeography and Lithofacies* (eds J.C.W. Cope, J.K. Ingham & P.F. Rawson), Memoir 13, pp. 87-96. Geological Society, London; Figure 13.5 - modified after La Tene Maps 2000; Figure 9.13 – courtesy of Tara Mines Ltd.; Figure 16.5 – after W. Warren, 1993; Figure 6.1 – modified after Williams H. 1983.*Tectonic elements of the restored North Atlantic. MUNCL, St.John's*; Figure 11.6 – modified after Wilson, H.E. *in* Holland (ed) 2001; Figures 10.3, 13.2, 13.3 – modified after N. Woodcock and R. Strachan (eds) 2000. *Geological History of Britain and Ireland*, Blackwell Science, 423 pp.; Figures 7.2, 7.4 12.2 - modified after Ziegler P.A. 1990. *Geological Atlas of Western and Central Europe*, 2nd Edn. Shell International Petroleum Maatschappij B.V., The Hague;

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