<gg-figure name=""></gg-figure>Chapter 3 An introduction to the geological history of Britain

The importance of sites

In the previous chapter, a variety of sites were introduced to illustrate the need for Earth heritage conservation. Evidence from many sites, where rocks and landforms were formed at different times and places, has allowed a historical sequence of geological events and previous geographies to be built up. These rocks and landforms at Earth heritage sites are still important for revealing new evidence, and for refining theories concerning their method and date of formation. To illustrate the importance of sites to the Earth sciences, three are described which show how information about Earth history can be inferred from the evidence they contain.

Salisbury Crags and Arthur's Seat, Edinburgh

Research began at this site over two centuries ago and the Crags played a most significant role in the early establishment of geological science. In Theory of the Earth (1795) James Hutton advocated the Vulcanist theory that the crystalline rocks of Salisbury Crags were formed by the intrusion and cooling of hot molten rock (magma) and not, as was the contemporary Neptunist view, as a precipitate from a primordial sea. Study and interpretation of the site was therefore vital in deciding the controversy between Vulcanists and Neptunists.

The igneous rock is sandwiched within sedimentary rocks which were baked as the molten rock intruded (Figure 8). Much of the overlying sedimentary rock has been removed by erosion and quarrying. An igneous rock mass, such as that at Salisbury Crags, which lies parallel to the beds is called a sill (*see* (Figure 12)).

The principle that processes observed today can be used to interpret those which occurred in the past is an important tool in Earth science. By making comparisons with contemporary active volcanoes and volcanic rocks, it is possible to find evidence in the Edinburgh area of former lava lakes, volcanic vents (now preserved as lava blocks in volcanic ash), numerous lava flows, volcanic ash layers and a sequence of lake sediments which accumulated within and adjacent to the volcanic vents. Arthur's Seat consists of two pipes of an ancient volcano which were active 350 million years ago. The site also shows the effects of earth movement, which has caused the eastward tilt of the rocks. The relationship between the original volcano and Arthur's Seat is shown in (Figure 8).

The site is now one of the most heavily used educational areas in Britain, and is of international significance as one of the most intensively investigated ancient volcanoes in the world.

Barton Cliffs, Hampshire

These cliffs (Figure 9) are internationally known for the rich and diverse fossil assemblage that they have yielded. These glaciated areas, the Earth's crust recovers, or rebounds, as the weight of the ice is removed. It is a complex process because three factors are involved: the ice itself is in retreat and allows the rising sea to flood the depressed crust, and the Earth's fossils and the sediments in which they are contained provide evidence for their contemporary environments. Comparisons with present-day environments assist this process further.

The abundant fossils at Barton Cliffs — molluscs, reptiles, mammals, birds and plants — have also enabled correlations to be made with rocks of similar age in other parts of the world. Thus the exposures at Barton are an international reference section or 'stratotype', and sediments all over the world of an equivalent age are called Bartonian, which corresponds to a span of time between 41 and 35 million years ago.

Islay and Jura, the Inner Hebrides

Raised cliff-lines, shore-platforms and shingle beach ridges, up to 30 metres above present sea level, occur along the coastlines of Islay and Jura in the Inner Hebrides (Figure 10). They provide evidence about changes in the relative levels of land and sea during the late-glacial period, at the end of the last ice age.

During an ice age, large volumes of ocean water become locked up in ice sheets and glaciers and, in consequence, the global sea level falls. In those areas actually covered by ice, such as Scotland, the weight of ice depresses the Earth's crust below the position of the modern sea level. At the end of an ice age, water is returned to the oceans by melting ice sheets and the global sea level rises. In the crust is also recovering. These processes occurred at variable rates. But when the rate of sea-level rise and the rate of crustal recovery were approximately the same, major shoreline features were fashioned. This happened at ocean levels below that of modern sea level. After the ice age, when the Earth's major ice sheets had melted, when sea level had been restored to its modern position and the Earth's crust had recovered to its pre-glacial position, the late- glacial shorelines were uplifted above modern sea level.

The late-glacial coastal features of Islay and Jura were formed when global sea level was below the present, and when the Earth's crust was locally depressed by the weight of the Scottish ice sheet. Both the global sea level and the Earth's crust of the Inner Hebrides have now recovered to their pre- glacial position. The coastal features that were formed between approximately 15,000 and 12,000 years ago, below the modern sea level, have been uplifted and now lie up to 30 metres above sea level.

The geology of Britain

Introduction

Geological maps provide the framework in time and space which permits stories from individual sites to be synthesised to produce the geological history of Britain. (Figure 11) is a simplified map showing the distribution of rocks across the British Isles. It does not show sands, gravels and other sediments deposited recently by rivers, or those left behind during the ice ages. Exploring this map and its key provides an insight into the immensity of geological time, and the origins of the great variety of rocks found over such a relatively small area of the planet.

The origin of rocks

The key to (Figure 11) is divided into three sections, reflecting the division of rocks into three major groups according to the way in which they were formed: sedimentary, igneous and metamorphic.

Sedimentary rocks

Weathering and erosion of pre-existing subsequently transported by rivers and marine currents to produce sediments such as sands and muds. After burial beneath further layers of sediment, these deposits become consolidated to produce sedimentary rocks such as sandstones, mudstones and shales. In addition to being formed from fragments of pre-existing rock, sedimentary rocks such as limestones are produced by accumulation of the calcareous skeletons of organisms, for example corals or bivalve shells (like those commonly seen on British beaches). For example, the accumulation of the microscopic calcareous skeletal elements of plankton produces a very fine-grained limestone known as chalk.

Igneous rocks

Rocks that have crystallised from molten material (magma) consist of individual interlocking angular mineral grains, unlike rocks at the Earth's surface yields a vast amount of rock debris that is sedimentary rocks, in which the mineral grains or rock fragments show some degree of rounding.

Igneous rocks may have cooled at the Earth's surface, in which case they are called extrusive (or volcanic, as in the key to (Figure 11)), or beneath the Earth's surface as intrusive rocks (Figure 12). Granite, granodiorite, gabbros and dolerite referred to in the key to (Figure 11) are all examples of intrusive rocks, whereas basalt, andesite and rhyolite are extrusive.

Metamorphic rocks

Rocks which have been altered from their original state by heat and/or pressure are known as metamorphic rocks. Such alteration occurs from several to tens of kilometres beneath the Earth's surface. Slates are grained metamorphic rocks formed from mudstones, and are included under sedimentary rocks in the key to (Figure 11). Schists and gneisses are coarser crystalline metamorphic rocks which formed deep within mountain belts.

Geological time

The key to the geological map shown in (Figure 11) subdivides sedimentary rocks into Cenozoic, Mesozoic, Palaeozoic Proterozoic. These terms correspond to particular spans of time (the numbers to the right of the key to (Figure 11) are ages in millions of years). The first three are called eras of geological time and together constitute the Phanerozoic Eon, which is characterised by rocks containing fossils of animals with mineralised skeletons. The term 'Phanerozoic' was originally coined from the Greek words for 'evident' and 'life'. The time before the Phanerozoic Eon is divided into two other eons, the Proterozoic and the Archaean, which together are often called the Precambrian. The term 'Upper Proterozoic' on the map refers to the most recent part of the Proterozoic Eon. The eras of the Phanerozoic are themselves divided into periods whose names are given in bold type next to the colour key (e.g. Permian, Cambrian). So for the sedimentary rocks, each colour represents rocks formed during a particular period.

Eons, eras and periods are shown systematically in (Figure 13) as time divisions of the stratigraphic column. The column is arranged in chronological order with the oldest period at the bottom and the youngest at the top, just as sedimentary rocks of these ages would be stacked now if they had been left undisturbed since they were laid down.

As stated in Chapter 1, Britain was the cradle of the science of geology, resulting in many of the divisions of geological time shown in (Figure 13) being named here by pioneering geologists, as shown in Table 1. These geologists realised that sediments deposited during a particular period of geological time are characterised by distinctive assemblages of fossils (*see* information box on page 19) which enable rock successions of the same relative age to be identified in many parts of the world. It may seem surprising that geologists do not use dates in the same way as historians. There are two main reasons. First, the periods within each of the eras were recognised by early geologists before there was any agreement about the age of the Earth, or the duration of the periods. The advent of methods of dating rocks using the small amounts of radioactive elements present in them enabled the relative scale represented by the periods to be calibrated in millions of years. But even today, this subdivision is not precise because of experimental errors and the different versions of such calibrations in use. This is the second reason that the names of the geological periods are used rather than dates — because it is less confusing than using numbers.

Fossils

(Figure unnumbered 1)

Palaeontology is the study of fossils. Fossils are the remains or 'traces' of plants or animals which have been buried by natural processes and then permanently preserved. These include skeletal materials (e.g. bones and shells), tracks, trails and borings made by living organisms, as well as their excrement. They also include the impressions (moulds or casts) of organisms on rock surfaces, and even actual biological material. For fossilisation to occur, the death of a plant or animal must normally be followed by its rapid burial, otherwise the remains will be physically broken up or destroyed by scavengers or by chemical and biological decay.

Once the organic trace has been buried it may be preserved as unaltered material, such as original skeletal material, mammoths frozen in permafrost or insects in amber. Alternatively it may be petrified. In this case, minerals have either replaced the previous cells or tissue, or filled in pores in the original material. Sometimes the sediment around a fossil may survive but the fossil itself is dissolved away, leaving a mould which may later become infilled with another mineral. This creates a cast of the original fossil.

Fossils are named in the same way as living plants and animals, and are important as a means of determining the relative ages of rocks. They can be used to reconstruct a detailed history of life on Earth and explain the rate and pattern of evolution and the nature of ancient environments and ecosystems. The importance of fossils is illustrated in the diagram.

Some geological patterns

Even a fairly superficial examination of the geological map of Britain shown in (Figure 11) reveals some significant patterns in the distribution of ages and types of rock that offer clues about the geological history of the area. South-east of a line between the mouths of the Rivers Tees and Exe there are broad bands of Permian, Triassic, Jurassic, Cretaceous and Tertiary rocks. This pattern is relatively simple compared with that displayed by older rocks to the north-west. The Permian–Tertiary rocks reflect the simple geological structure underlying this area. For example, north of London, the rock layers are inclined gently (by a matter of a few degrees) to the east and south-east, and so are younger in these directions. London is situated in the centre of a 'basin' in which rocks of Tertiary age are preserved. This is because a broad fold, termed a syncline exists here. To the south of the London Basin another fold occurs, bending the strata upwards into an arch, or anticline, so that older strata are exposed in the Weald (Figure 14). The North and South Downs are the topographic expression of the Wealden Anticline, produced respectively by northward and southward inclinations of the Chalk. The Chalk extends beneath the London Basin, reappearing to the north-west, where it forms the Chiltern Hills (here, it is inclined to the south-east).

The regions exhibiting more complex patterns visible in the western and northern areas of (Figure 11) are generally highland areas (Figure 15). These are formed of Palaeozoic or older rocks, from sedimentary, igneous and metamorphic origins. These harder rocks are more resistant to erosion than the Mesozoic and Tertiary sedimentary rocks to the east and south-east. In fact, these areas are relics of former mountainous areas comparable in grandeur with the Alps or Himalayas of today.

Mountain building episodes

(Figure 16) shows the distribution of rocks in Britain associated with mountain building episodes. The Caledonian mountain belt resulted from the closure of a proto-Atlantic ocean between 'North America' and 'Greenland' and 'Europe'. The Variscan mountain belt was formed by closure of a former ocean which separated southern 'Britain' and most of 'Belgium' from the rest of 'Europe'. By closing the present-day Atlantic Ocean (Figure 17), the distribution of rocks caught up in these two mountain building episodes shows that they were once relatively long but narrow regions. The global pattern of crustal movements that causes mountain building (often referred to as 'orogenesis') is explained on the following pages.

Mountain building results in the deformation of previously deposited sediments and volcanic rocks to produce complex fold structures. This deformation also results in the thickening of the Earth's crust, so that some rocks are buried deep beneath the Earth's surface, where extremely high temperatures and pressures produce metamorphic rocks. The thickening of the crust results in uplift, as the rocks that comprise mountain belts are less dense than those beneath, and so they 'float' on deeper layers, much like an iceberg floats in water. As with icebergs, the deeper the submerged part, the higher the relief at the surface.

Mountain building and plate tectonics

As already stated, mountain building is linked to the closing of former oceans. Today (and in the geological past) oceans are floored by crustal material that has a greater density than continental crust. As shown in (Figure 18), the crust forms the thin outer skin of the Earth. Beneath it, in a concentrically layered structure, is the mantle and the core. So the Earth is rather like a spherical avocado pear. The thin green skin represents the crust, the yellow flesh the mantle, and the stone at the centre the core.

It is known from a variety of lines of evidence (including direct measurement from satellites) that horizontal movements occur in the Earth's crust. In fact, different parts of the crust move in different directions. The crust consists of a series of slabs or tectonic plates: where they collide or move apart, there are zones of earthquakes and volcanic activity, but there is little activity away from the boundaries between the plates.

(Figure 19) shows the plate boundaries associated with South America and Africa, two continents that are moving slowly apart at about four centimetres per year — twice the rate at which human fingernails grow. This means that the South Atlantic is getting wider. In fact, new oceanic crust is being formed along the Mid- Atlantic Ridge as basaltic magma wells up from the mantle to form both intrusive and extrusive igneous rocks. The ridge is associated with a narrow zone of shallow earthquakes.

To the west of South America, the Pacific oceanic crust is moving eastwards, plunging beneath the continental crust, where it enters a hotter region and begins to melt. The resultant magma rises upwards, melting some of the continental crust on its way to produce granites. Some of the magmas, which are very viscous, do reach the surface and cause explosive volcanic activity. This plate collision zone is also characterised by a zone of earthquakes beneath South America, as well as an ocean trench and the Andean mountain belt.

(Figure 20) shows the distribution of the crustal plates around the world. Most of the plate boundaries shown on this map fall into three categories — constructive, destructive and conservative — and can be described as follows:

Constructive plate boundaries: where basaltic magma rises from the mantle to form ocean ridges such as that running down the middle of the Atlantic. They are also characterised by shallow earthquakes (down to 5 km depth).

- Destructive plate boundaries: where oceanic crust plunges beneath continental crust. This process is called subduction: it is associated with deep ocean trenches and an inclined zone of earthquakes down to depths of several hundred kilometres. Subduction results in the melting of crustal material which rises to form plutons (*see* (Figure 12)) within the overlying continental crust, and if they reach the surface they cause explosive volcanic activity. Destructive plate boundaries also occur where two slabs of continental crust collide (such as in the Himalayan region today). Most of the Pacific Ocean is ringed by destructive plate margins; on its western side many such margins are marked by ocean trenches and associated volcanic islands arranged in an arc-like pattern, such as the Japanese islands.
- Conservative plate boundaries: where plates slide past each other, causing shallow earthquakes (the best known example is the San Andreas Fault in California).

What causes the movement of crustal plates? Basically, plate movement is the mechanism by which the Earth loses its internal heat generated by the breakdown of radioactive elements present in the crust and mantle. The internal heat drives a series of convection currents in the mantle which in turn dr ive plate movement (Figure 19), although the exact linkage between the cur rents and the plates is not clear. Are the y pushed apar t along constructive boundaries, or pulled down along destructive boundaries? As yet there is no consensus among Earth scientists.

(Figure 21) shows, in cross-section, an idealised sequence of events in a cycle of ocean opening and 'closing', culminating in mountain building. As the mountain belt is uplifted it is eroded, and sediments derived from it are deposited in neighbouring lowland areas, or in new oceans formed nearby if the continental crust splits up once more. As the mountains are eroded, they become partly covered by sedimentary rocks which overlie the older deformed rocks with an angular discordance, producing a major unconformity (*see* (Figure 29)) and (Figure 37).

Thus plate tectonics is the driving force behind mountain building. The formation of new oceans and their subsequent 'closure' produce a variety of rock types and structures that enable past plate tectonic processes to be interpreted from the rock record. At destructive plate margins, sedimentary rocks are folded, faulted and deeply buried, leading to metamorphism. Igneous processes along such margins result in the formation of huge masses of intrusive igneous rocks above which explosive volcanoes occur. Most of the granite shown on the geological map in (Figure 11) was produced at destructive plate margins. All these processes result in thickening of the crust, which then rides higher on the underlying mantle to produce mountain belts. Such uplifted areas are affected by increased rates of erosion, and sediments accumulate on the margins of the newly deformed continental crust. The Devonian and Triassic sediments shown in (Figure 11) were respectively derived largely from the uplifted Caledonian and Variscan mountains.

A geological history of Britain

The Precambrian rocks of Britain

Over 85% of Earth history is represented by the Precambrian Era, the time between consolidation of the Earth's crust and the beginning of the Cambrian Period, about 570 million years ago. Less is known about these rocks than those formed during the last 570 million years of the geological history of Britain, because most of the early rocks have been eroded, deformed, metamorphosed or buried beneath younger rocks. No trace has yet been found anywhere on Earth of rocks which date from the first 600 million years of the Earth's history, but rocks and minerals approximately 4000 million years old have now been a found in most of the major continents. These rocks provide evidence of the nature of the early Earth.

During the Precambrian there was more rapid movement of the plates of the crust because of higher levels of heat production (caused by radioactive decay) and because the crust was still forming and was thinner. Consequently, many Precambrian rocks have undergone at least one episode of mountain building (orogeny), and some may have undergone several.

The oldest Precambrian rocks to be found in Britain are the Lewisian gneisses ((Figure 22)a, coloured pink in (Figure 11)), in the north-west Highlands and the Western Isles. They were formed over a period of 2,000 million years and the oldest were formed some 3,300 million years ago. These gneisses show evidence of several episodes of deformation and the intrusion of igneous rock, both associated with mountain building. These early crustal rocks were later overlain by Torridonian sediments, and the Moine and the Dalradian metamorphic rocks that show evidence of a long and complex geological history. These underlie large parts of northern Scotland (grey- green in (Figure 11)). Sedimentary and volcanic rocks of Precambrian age are also found in Anglesey (Figure 22)b, the Welsh Borders, the Malverns and the Midlands.

Rocks which formed at the end of the Precambrian show evidence of animal life, and jellyfish-like fossils can be found in the Precambrian rocks of central England (*see* (Figure 3)) and parts of Wales.

Since the Precambrian, continuing major continental movements first created and then dispersed a single giant supercontinent, known as Pangaea (Figure 23). This single continent formed a vast landmass, the assembly and dispersal of which has left a marked imprint upon Britain's geological record. During this time, the crust on which 'Britain' was situated drifted northwards as a result of plate movements (Figure 24).

The Cambrian, Ordovician and Silurian rocks of Britain

Rocks of the Cambrian Period, found in Scotland, originally formed part of a North American continent, and were separated from the Cambrian rocks of England and Wales by a wide ocean, the Iapetus (*see* (Figure 23)a). The fossil record of these rocks includes trilobites, a now extinct group of arthropods, graptolites (*see* (Figure 39)) squid-like nautiloids and other types of mollusc, demonstrating that there was a wide range of animal life in this ocean. The Iapetus Ocean reached its greatest width early in the Ordovician Period and later began to narrow. Enormous thicknesses of muddy sandstones were deposited on the margins of the ocean. As the ocean narrowed, arcs of volcanic islands developed in the 'Lake District' (Figure 25) and 'North Wales'. Mountain building began in Scotland at this time.

Later, in the Silurian Period, the development of coral reefs indicates a shallowing of the ocean. The Silurian fossils show none of the geographic differences characteristic of the Cambrian and Ordovician periods, because by this time species could move freely between either side of the shrinking Iapetus Ocean. At the end of the Silurian, the climax of the Caledonian period of mountain building occurred as 'Scotland' and 'England' finally collided.

The Devonian and Carboniferous rocks of Britain

The Caledonian mountains were rapidly eroded and great thicknesses of sediment, now known as the Old Red Sandstone, accumulated over much of northern 'Britain' and south 'Wales' during the Devonian Period. In 'Devon' and 'Cornwall' the land was bordered by tropical seas which persisted through the Devonian and Carboniferous periods (*see* (Figure 23)).

The Devonian continent supported freshwater lakes with many fish species. Sediments which formed near hot mineral-rich springs at lake edges, about 370 million years ago, have been found at Rhynie in Scotland (*see* (Figure 46)). These contain the remains of the oldest-known higher plants in the world. Insect and arachnid fossils are also found here, demonstrating that the land was being colonised rapidly at that time.

During the early part of the Carboniferous Period the remnants of the Caledonian mountains were flooded by a warm tropical sea in which thick layers of limestone were deposited. In the late Carboniferous huge deltas invaded this sea. On the surface of the deltas dense forests of giant horsetails, tree-ferns, giant clubmosses flourished. The remains of these trees were sometimes buried, to be transformed later into coal (Figure 26). Dragonflies, with a wing span of up to 60 centimetres, and other insects and arthropods were common in these forests, and the first amphibian-like reptile fossils, which are about 340 million years old (Figure 27), have been found in Carboniferous rocks in Scotland.

Towards the end of the Carboniferous Period, a northward-moving plate collided with the southern margin of the Old Red Sandstone Continent in south- west 'England'. This was the final event in the construction of the supercontinent Pangaea (*see* (Figure 23)c) some 300 million years ago, and caused the Variscan Orogeny (Figure 28). The granites of south-west England were intruded at this time.

The Permian and Triassic rocks of Britain

Desert conditions prevailed over much of Pangaea during these periods. Vast areas of sand dunes were preserved as the 'New Red Sandstone' (Figure 29). During the Permian Period an inland sea occupied much of the area of what is now the North Sea, and when it began to dry up, evaporite deposits were precipitated (*see* (Figure 48)).

The drier conditions led to evolutionary changes in the animals and plants. Forests of conifers and cycads (the sago palm is a modern cycad) began to replace the earlier plant-forms, and about 300 million years ago the reptiles became more prolific.

The Jurassic and Cretaceous rocks of Britain

At the beginning of the Jurassic Period much of 'Britain' was flooded by a warm sea teeming with life. In Britain, shallow-marine Jurassic rocks occur in a belt from Dorset to Yorkshire, in South Wales and in scattered patches in the islands of north-west Scotland and in northern Scotland (olive-green in (Figure 11)). The fossil record of these rocks demonstrates that cephalopods were particularly abundant, especially ammonites and bullet-shaped belemnites. Bivalve and gastropod molluscs, sea urchins and fish were also plentiful. Large marine reptiles such as ichthyosaurs and plesiosaurs were numerous (Figure 30)a. The reptiles also flourished on the land and evolved into many forms, including the dinosaurs (Figure 30)b. By about 210 million years ago, the first mammals had evolved, and 150 million years ago the first true birds appeared, although they were a relatively insignificant part of the fauna at the time.

Thick deposits of calcareous ooze, formed from the remains of plankton, accumulated in the late Cretaceous seas over much of 'Britain'. These became the Chalk which is now only found in eastern and southern Britain (Figure 31) and Northern Ireland. Towards the end of the Cretaceous Period, sea levels reached an all-time high and most of 'Britain' was submerged beneath the sea.

During the Triassic and Jurassic periods, the supercontinent of Pangaea began to be slowly pulled apart (*see* (Figure 23)), a process which accelerated in Cretaceous and Tertiary times.

The Tertiary rocks of Britain

The fossil record indicates that many plants and animals became extinct at the Cretaceous–Tertiary boundary about 65 million years ago. This mass extinction was perhaps the result of a global catastrophic event, such as a meteorite impact or major volcanic eruption. On land the dinosaurs and pterosaurs became extinct, but in the Tertiary Period the mammals diversified and flowering plants began to predominate at the expense of the earlier plant types. In the sea, gastropods and bivalve molluscs proliferated, but the ammonites, belemnites and many types of marine reptile became extinct.

As the Atlantic Ocean opened between 'Greenland' and 'Scotland', a chain of volcanoes erupted, flooding the landscape with extensive lava flows. Their eroded remnants can now be recognised on Skye (Figure 32), Rum, Mull, the Ardnamurchan Peninsula, Arran and in Antrim. Later, 'Africa' collided with 'Europe' to form the Alps. The effects of this mountain building episode can be seen in the fold structures of southern Britain (*see* (Figure 14)).

'Britain' continued to move northwards from the tropics into the cooler mid-latitudes (*see* (Figure 24)).

Quaternary sediments and landforms of Britain

The long geological history of Britain has influenced its landscape, but much of its present shape was fashioned during the Quaternary Period ('Great Ice Age'), during the last two million years or so. The Quaternary consisted of several ice ages separated by temperate interglacial climates. During the ice ages, glaciers grew in the mountains and occasionally large ice sheets advanced into lowland 'Britain'. On one occasion, ice extended as far south as 'London' (Figure 33).

Early in the Quaternary Period, these ice ages occurred about every 41,000 years, when the uplands of England, Scotland and Wales were probably entirely ice-capped on each occasion, although the evidence has been destroyed by later glaciations. Over the last 900,000 years, however, the rhythm of the major ice ages changed and they have occurred about every 100,000 years. It was during this time that major glaciations greatly modified the landscapes of Britain (Figure 34). As well as eroding deep valleys, the ice sheets deposited clays, sands and gravels, producing landforms such as eskers and drumlins, as well as a widespread mantle of boulder clay ('till') across parts of the country (Figure 35).

Areas beyond the ice-sheet margins were affected by frost, ice and wind, in a cold and dry climate, like the Arctic of today. Such conditions are called 'periglacial'. Slopes were attacked by freezing and thawing processes to create rock debris and produce a widespread layer of periglacial deposits. Rivers were unable to transport all of this material, so deposition occurred on wide floodplains with braided channels. Extensive periglacial gravel deposits are widespread in southern England.

During the ice ages, global sea levels were relatively low because ocean water was locked up in the ice sheets. For example, at the peak of the last ice age, some 22,000 years ago, the sea level was approximately 120 metres below that of today. Thus, 'England' was joined to 'Europe' at that time.

In the glaciated areas of Britain, the weight of the ice depressed the Earth's crust. When the ice retreated, and before the crust 'rebounded' to its former position, the sea fashioned shorelines at levels relatively lower than at the present. When the crust finally returned to its pre-glacial level, such shorelines were uplifted above present-day sea level to form 'rebound' raised beaches. There are many such beaches in Scotland (*see* (Figure 10)).

Ice-age conditions were separated by periods of temperate interglacial climate, when Britain was sometimes at least as warm as today, and mixed oak temperate forests became established. During the interglacials there was less ice on the Earth's surface and beaches formed at times of relatively high sea level. These are now found in southern Britain. Many have been raised by gradual long- term uplift.

The flora and fauna of Britain responded to the climatic changes during the Quaternary Period. Variations in the type and distribution of plants and animals have been reconstructed from fossil remains, including pollen grains and fossil bones preserved in peat bogs, as well as lake and cave sediments. This is evident at sites such as West Runton, Norfolk, for example (Figure 36).

Fossils of mammals such as hippopotamus, rhinoceros, elephant, cave hyena, woolly mammoth and early humans have been found in Britain. In the raised beach deposits at Boxgrove, West Sussex, hominid remains (a tibia bone and a tooth) and stone tools have been estimated at between 400,000 and half a million years old. At Swanscombe, in Kent, a skull intermediate in form between Homo erectus and Neanderthal Man has been found in sediments about 400,000 years old. Stone tools of an even older age have also been found at High Lodge, Suffolk, and Torquay, Devon.

Britain after the last ice age

Following the disappearance of the last upland glaciers from Britain 11,500 years ago, a succession of vegetation communities recolonised the land and geomorphological processes continued to modify the landscape. On the coast, erosion and deposition caused by variations in the relative level of land and sea as well as the variability of coastal processes, led to changes in the shape of coastlines. Beaches, dune systems and shingle structures also developed where there was a ready supply of sediment. Inland, slopes left after the ice had melted were affected by mass-movement processes, from soil- creep to landslides, while rivers cut channels through the glacial, and other, sediments on valley floors.

The water released to the oceans from the melting of ice sheets in Eurasia and North America flooded any connection between Ireland and Britain. Britain also became separated from continental Europe. At that point, further natural colonisation of plants and animals from the continent was inhibited.

Changes in vegetation over the last 11,500 years are shown by pollen and other plant remains preserved in bogs and lake deposits. The sequence of sediments at such sites can also be used to infer changing environmental conditions and to provide baseline information against which past and present human impacts on the environment may be assessed.

Present-day Britain

Contemporary geomorphological processes cause changes that are, perhaps, not as dramatic as they were during the ice ages.

But coastal and river processes can cause major changes over only a few centuries, or even catastrophically, as in the case of the Exmoor floods and North Sea storm-surge flooding, both in 1953. Other examples of geomorphological activity today include weathering and mass- movement processes.

British landscapes have been further diversified by human activity, which has modified slopes and rivers, and provided a cultural overlay of a series of landscapes altered over many historical periods. Historically, perhaps the greatest changes have been those of marsh and heath reclamation, woodland clearance and the development of agricultural field systems.

The importance of Britain in the development of geology

The record of Earth history has been assembled by the careful accumulation and consideration of evidence from the Earth's rocks. British natural historians, scientists and scholars played a pioneering role in developing the sciences of geology and geomorphology. The wealth of evidence in Britain's landscape enabled them to develop their ideas and theories. A brief account of the early development of geological science is given here to show how important Britain's Earth heritage was in developing the principles of geology.

During the latter part of the eighteenth and the early part of the nineteenth centuries, major advances in geology occurred. In 1795, James Hutton published *Theory of the Earth*, which is regarded as the first concerted attempt to explain geological phenomena in scientific rather than biblical terms. Hutton defined the principle of uniformitarianism, which is the proposal that processes observed today can be used to interpret the past. He recognised the operation of processes over long periods of geological time and cycles in Earth history (Figure 37). Some of his ideas were developed by John Playfair in his *Illustrations of the Huttonian Theory of the Earth* (1802). Playfair used British examples, particularly relating to the gradual, fluvial origins of valleys, a novel concept at a time when catastrophic theory (based on the biblical f lood in Genesis) dominated. Hutton's work was later developed by Charles Lyell, an immensely influential figure. In *The Principles of Geology* (1830), he provided a theoretical basis for geology by applying the principles of uniformitarianism.

In 1807 the Geological Society of London was founded, the first geological society in the world. It became a centre for geologists to meet to discuss new discoveries and theories. Not long afterwards, in 1815, William Smith, a land surveyor and civil engineer, published a geological map of England and Wales, based on principles developed from his early observations around Bath, including canal excavations. There he established a system of correlating rock strata by comparing their fossil contents. This became the basis of modern stratigraphy. He was described by the President of the

Geological Society, at an award ceremony in 1831, as 'the father of English geology'.

In 1835 the Geological Survey of Great Britain was established, the first in the world, to carry out detailed geological mapping of the whole country. Its first Director, Sir Henry de la Beche, produced the first survey memoir, describing the metalliferous ore fields of south-west England. In 1837 the Survey was given accommodation in London, which included a Museum of Practical Geology. In 1934 the museum relocated to South Kensington, where it now forms the Earth Galleries of the Natural History Museum.

In the 1830s, Sir Roderick Impey Murchison began a study of the rocks of south and central Wales. He compared rocks at different localities by means of the fossils they contained, including different species of trilobite. In 1858 he published *Siluria*, naming this sequence of rocks after an ancient Celtic tribe, the Silures. Meanwhile, Adam Sedgwick was investigating the rocks of the Lake District and North Wales. These are older than the rocks that were studied by Murchison and contain some of the oldest fossils in Britain. He named these rocks the 'Cambrian', based on the Latinised Welsh name for Wales *Cymru*. As a consequence of their further studies in south-west England together they named the Devonian System (Figure 38). Murchison and Sedgwick also discovered fossil fish in the Devonian Old Red Sandstone of Scotland. These finds were added to by Hugh Miller and Louis Agassiz, who were able to portray the nature of the freshwater fish of the Old Red Sandstone.

Although some Cambrian and Silurian rocks as originally defined by Murchison and Sedgwick were quite distinct, others contained similar assemblages of fossils. A controversy erupted between them which was not resolved until after their deaths. Subsequently, Charles Lapworth, a clergyman, spent his spare time studying the rocks around Galashiels in southern Scotland. He looked particularly at graptolite fossils (Figure 39). In comparing his findings with those of Murchison and Sedgwick, he concluded that the overlapping strata were sufficiently distinct to represent a separate period, thereby resolving the earlier controversy. He named this the Ordovician, after the Ordovices, another Celtic tribe which inhabited part of Wales. Thus the Cambrian, Ordovician, Silurian and Devonian Periods were all named in Britain.

In the 1820s Mary Anning collected and sold Jurassic fossils in Lyme Regis, Dorset (Figure 40). She discovered remarkably complete specimens of the marine reptile *Ichthyosaurus*; the first- known articulated skeleton was discovered by her when she was a girl of eleven. She also found the first almost complete *Plesiosaurus* skeleton in 1823 and remains of the flying reptile *Dimorphodon* in 1828. These finds proved to be important for the study and interpretation of the evolution of reptiles.

In 1822, Mary Ann Mantell discovered fossil teeth in the Cretaceous Wealden rocks while walking in Ashdown Forest, Sussex. These were later identified as those of a large herbivorous reptile, Iguanodon. In 1824, a fossil thigh bone came into the hands of Professor William Buckland, who named the animal *Megalosaurus*, later discovered to be a large carnivore. Further finds included fossils of the armoured *Hylaeosaurus*, described by Charles Mantell (Mary Ann's husband) in 1832, and a large sauropod dinosaur, *Cetiosaurus*, from the Oxford Clay near Peterborough. In 1841, at a meeting of the British Association for the Advancement of Science, Dr Richard Owen first suggested that *Iguanodon*, *Megalosaurus* (*see* (Figure 43)) and *Hylaeosaurus* should together be called the *Dinosauria*. Thus it was the discoveries of British fossil reptiles which led to the naming of this group.

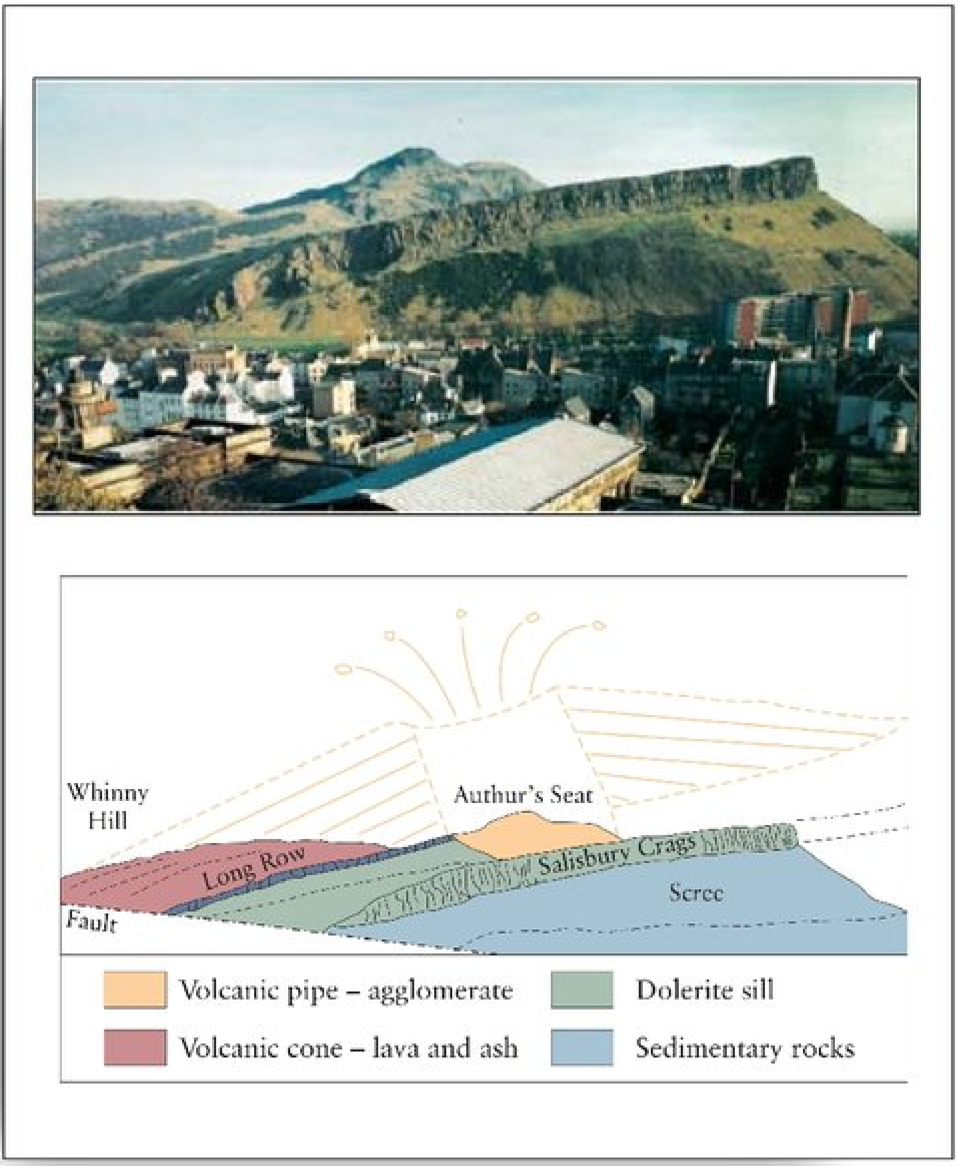
Significant advances in the understanding of ice ages and landscape changes were also made in Britain during the nineteenth century. In the early 1840s the evidence of glacial landforms in Scotland made a significant impression on the Swiss geologist Louis Agassiz, a leading figure in advancing 'the Glacial Theory'. He helped develop thinking on the possibility of glaciation in areas where there were no modern glaciers. In 1842 Charles Darwin and William Buckland also confirmed the ideas of Agassiz in Wales. Robert Jamieson and Charles Maclaren played an important part in the wider dissemination of the ideas Agassiz advocated, together with those of other early glacialists.

Maclaren is also credited with first recognising the sea-level changes associated with glacio- eustasy (changes in global sea level as water, once locked up in ice sheets, was released on subsequent melting). Thomas Jamieson was the first to recognise complementary glacio-isostatic changes in sea level ('rebound' of continental crust when the weight of ice which depressed it is removed upon melting of the ice). His conclusion was based on detailed studies of raised beach deposits in the Forth Valley.

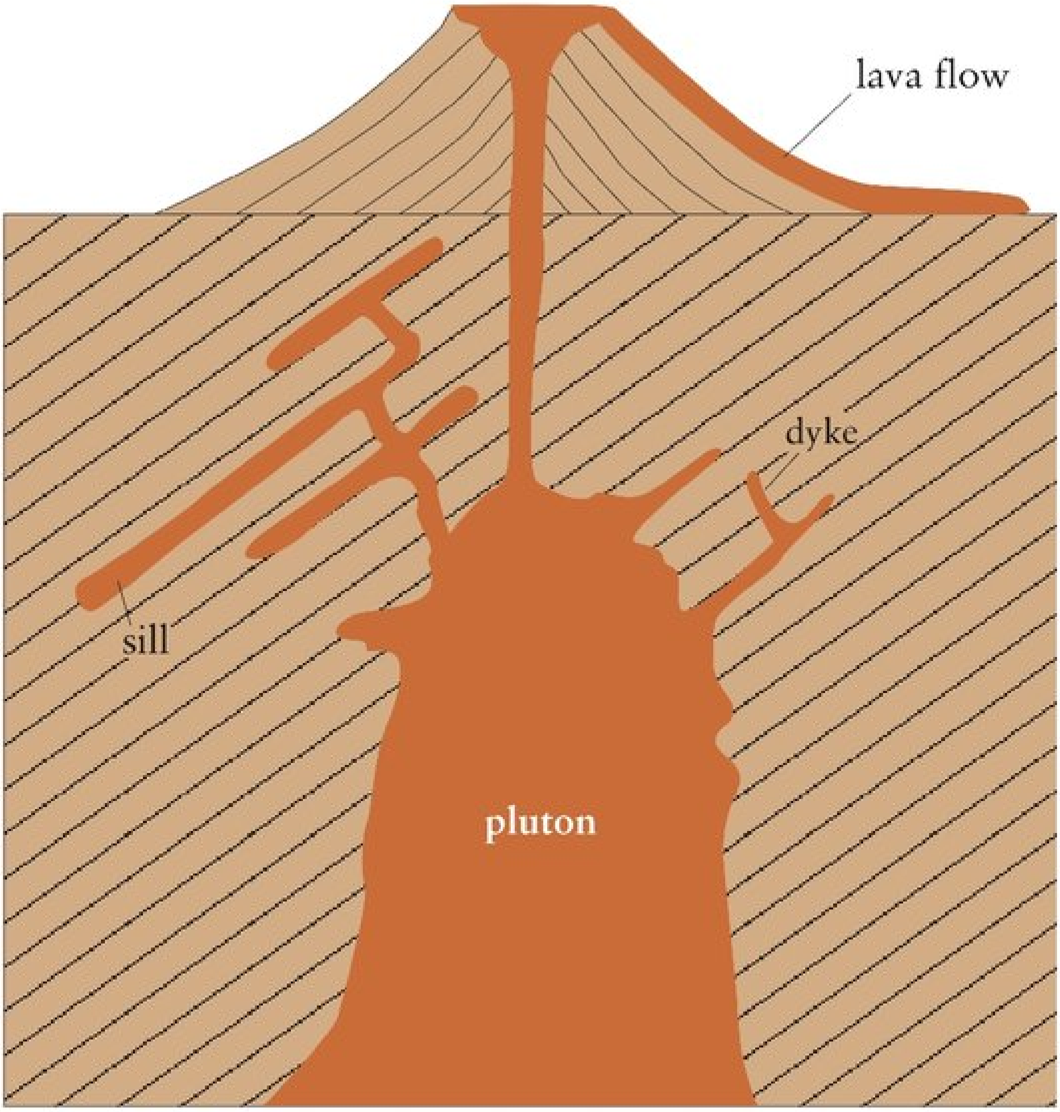
Archibald Geikie, Director General of the Geological Survey, Andrew Ramsay and James Croll identified multiple phases of glaciation in the sedimentary record. Croll also recognised that the changes in climate were controlled by variations in the Earth's orbit around the Sun and that ocean currents played a major part in heat transfer from the tropics to higher latitudes. Geikie contributed significantly to the understanding and interpretation of the links between geology and geomorphology. His younger brother, James, published *The Great Ice Age* in 1874, a highly influential book with an international perspective on the Ice Age.

During the nineteenth and twentieth centuries the Geological Society of London, the British Geological Survey and the universities, amongst others, advanced the study of geology and geomorphology in Great Britain. Knowledge of the geological column has been refined by international collaboration, which has also facilitated the correlation of geological events in Britain with those elsewhere. At the same time, our understanding of the geological and geomorphological processes which have been at work throughout the period of geological history continues to be deepened, and methods for locating economic resources below ground also continue to be developed and refined.

References and further reading



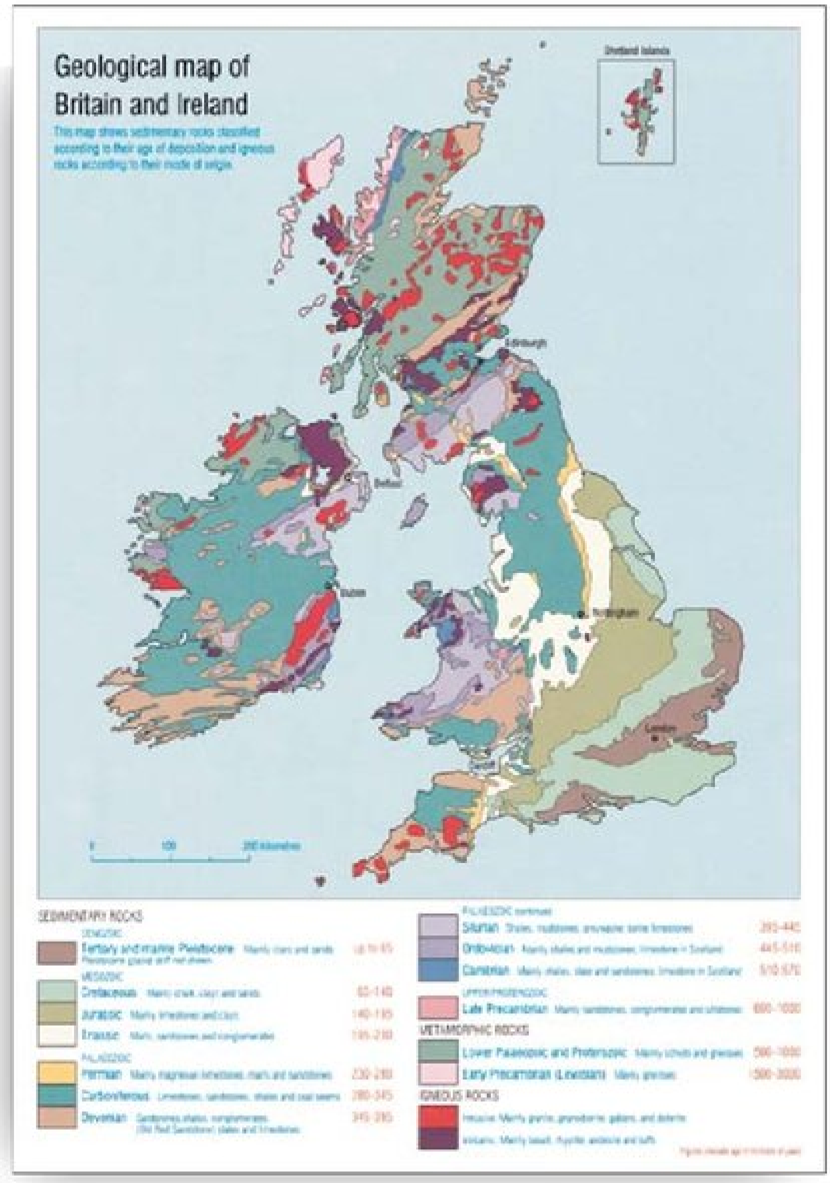
(Figure 8) Salisbury Crags and Arthur's Seat, Edinburgh. The diagram shows the relationship between the geology and the ancient volcano. Photograph reproduced by permission of the Director, British Geological Survey. NERC copyright reserved. Diagram after Wilson (1994).



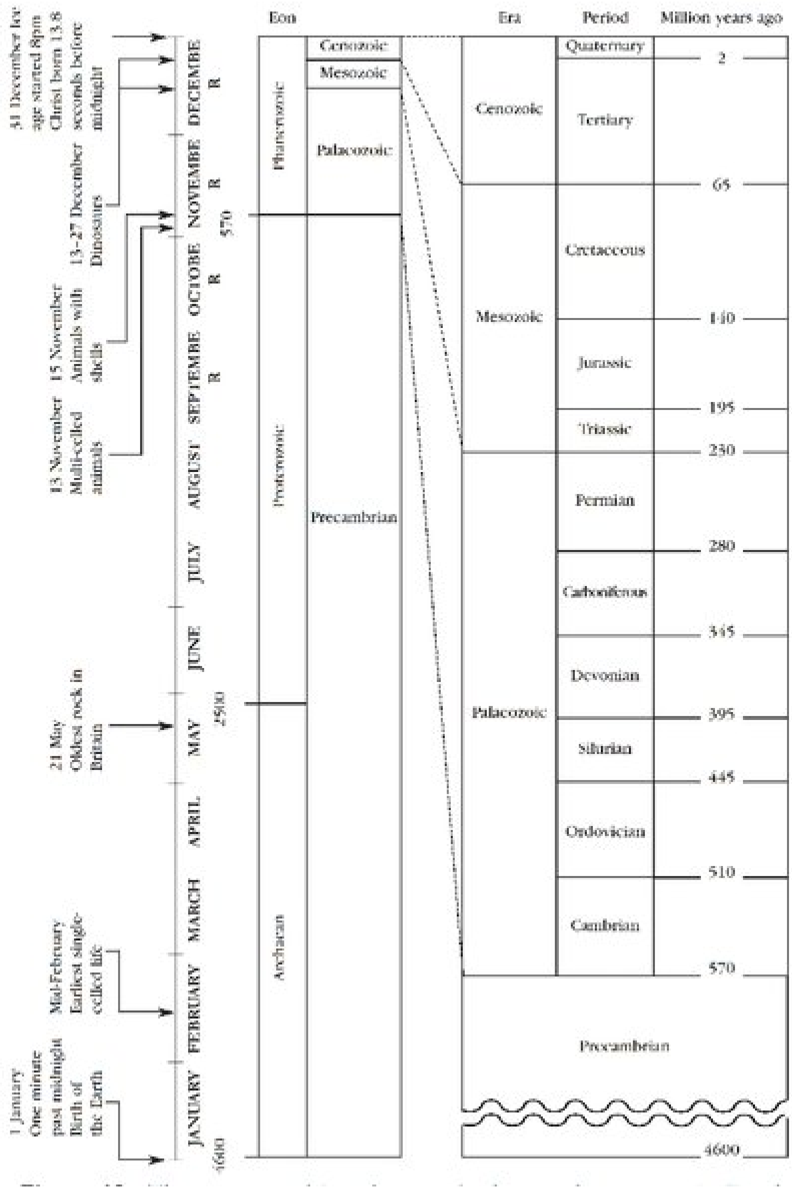
(Figure 12) The principal occurrence of igneous rocks. Extrusive: lava flows; Intrusive: sills, dykes and plutons. Molten rock erupting from volcanoes may also produce ash (referred to as tuff in the key to (Figure 11)). After Wilson (1994).

(Figure 9) Cliffs near Barton-on-Sea, Hampshire. The cliffs are made up of sediments deposited in marine, brackish and freshwater environments. Where these sediments occur inland, there are no natural outcrops, the land largely being built over or farmed, and there are few opportunities to see vertical sections through the strata. On the coast, however, fresh sections occur as the sea erodes the cliffs, but they can be obscured by coastal defence works and landslides. Photo: C.D. Prosser.

(Figure 10) The coasts of the islands of Islay and Jura in the Inner Hebrides display raised ice-age shorelines, especially spectacular shingle beach ridges. At one locality, up to 31 unvegetated shingle ridges occur up to 30 metres above present sea level. These were formed at the end of the last ice age, when sea level and the level of the Earth's crust in the Inner Hebrides were below modern sea level. These late-glacial shorelines and shingle ridges were uplifted to their present position when the Earth's crust recovered from the load of the ice sheet. Photo: J.E. Gordon.



(Figure 11) Geological map of Britain and Ireland. Each period, although represented on the map by a single colour, may include a variety of rock types. For example, the Silurian (pale mauve) includes shales and mudstones, and the Jurassic (olive-green) includes limestones and clays. This simplification is necessary to be able to show the geology of Britain on such a small map. See glossary for definition of terms. Reproduced by permission of the Director, British Geological Survey. NERC copyright reserved.



(Figure 13) The stratigraphic column. At the top, key events in Earth history are compressed into one year to illustrate the immensity of the geological timescale. After Grayson (1993). The stratigraphic column is the array of geological time units that results from stacking them vertically, with the oldest at the base, overlain by successively younger units. In the 1830s, Sir Charles Lyell recognised that in the Cenozoic (sometimes spelt Cainozoic) Era modern species appear as fossils, becoming progressively more abundant in younger sediments. For example, 3% of Eocene species are alive today, and as many as 30–50% of Pliocene species exist today. Lyell chose to use Greek prefixes to subdivide the Era according to this observation. After Wilson (1994).

Geological Conservation Review sites within Sites of Special Scientific Interest

The 3002 Geological Conservation Review sites identified will be considered for notification as approximately 2300 SSSIs. The difference in numbers reflects the fact that Geological Conservation Review sites chosen as parts of different blocks may partly or entirely overlap geographically. A single SSSI may encompass several Geological Conservation Review sites, as well as one or more features of special biological value. The diagram below shows GCR site overlaps within a single hypothetical SSSI.

Durlston Bay SSSI, South Dorset, is a good example of a large composite site which incorporates separate and overlapping Geological Conservation Review sites.

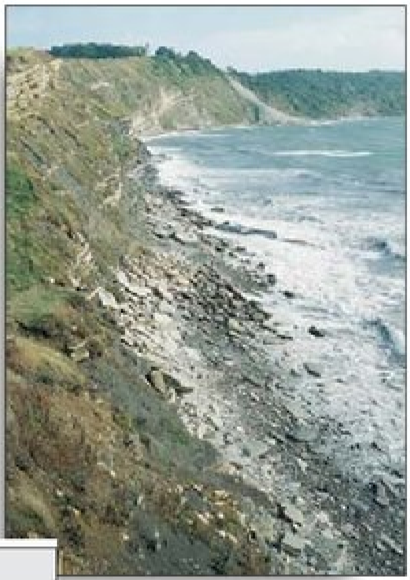
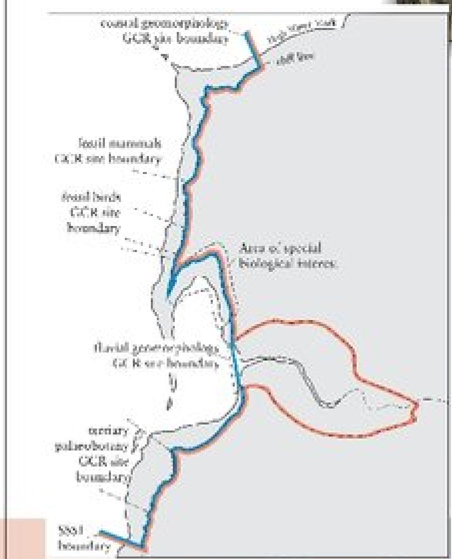


Photo: J.G. Larwood.

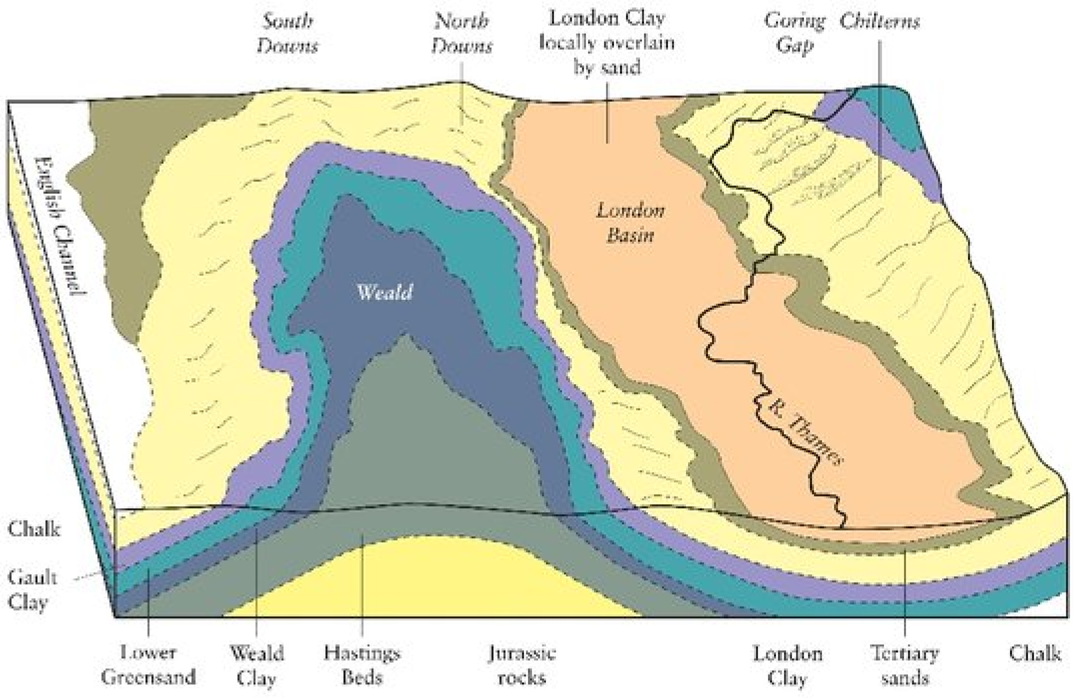


Special features of interest found at Durlston Bay have led to the sites' inclusion in six Geological Conservation Review blocks, as follows:

- Portlandian-Berriasian Stratigraphy
- Mesozoic Mammalia
- Palaeoentomology
- Mesozoic-Tertiary Fish/Amphibia
- Jurassic-Cretaceous Reptilia
- Coastal Geomorphology of England.

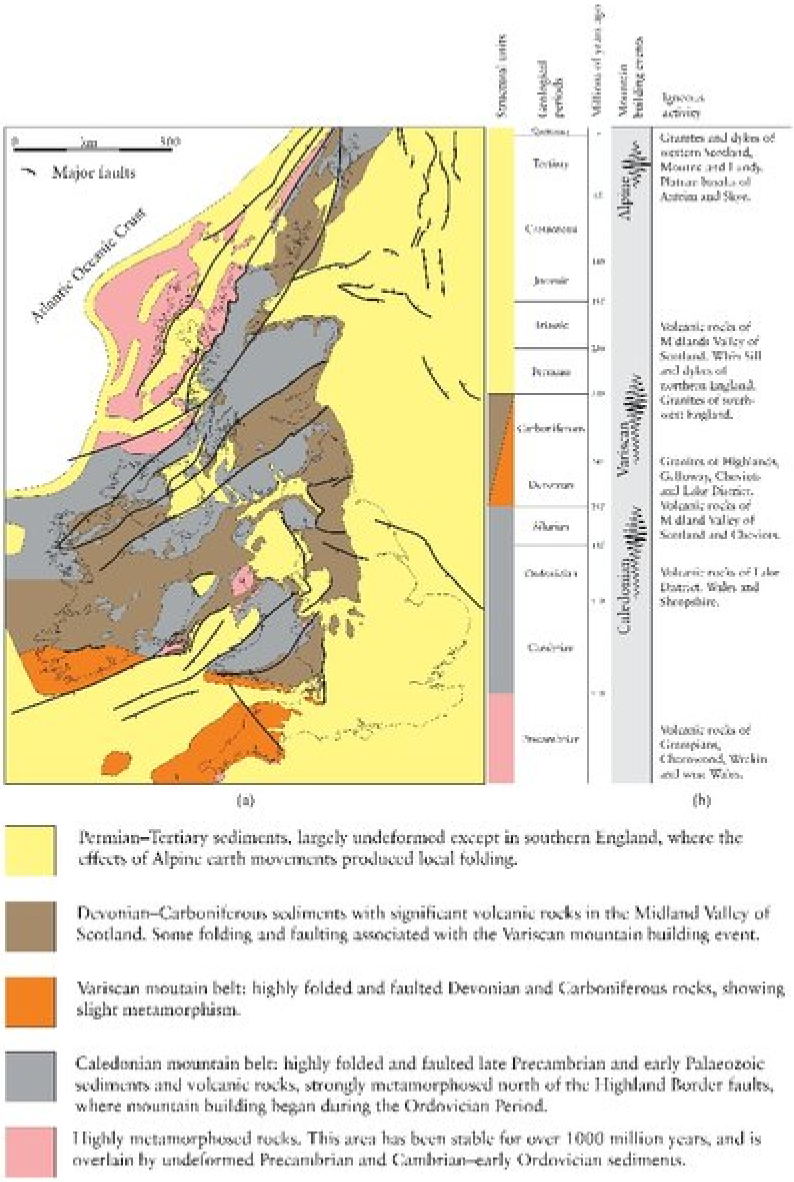
Each of the six Geological Conservation Review sites within the single Durlston Bay SSSI was assessed independently for inclusion within its respective network, and judged worthy of Geological Conservation Review status in its own right.

(Figure unnumbered 1) The photograph shows a fossil ammonite, Asteroceras obtusum, from Charmouth, Dorset. Although superficially like a snail shell, it is actually the remains of a cephalopod. Modern relatives include the squid, octopus and Nautilus. Because of the relative abundance of ammonite fossils, and the relatively rapid evolution of different species, they provide useful 'markers' for comparing ages of rocks at different places. Photo: K.N. Page.

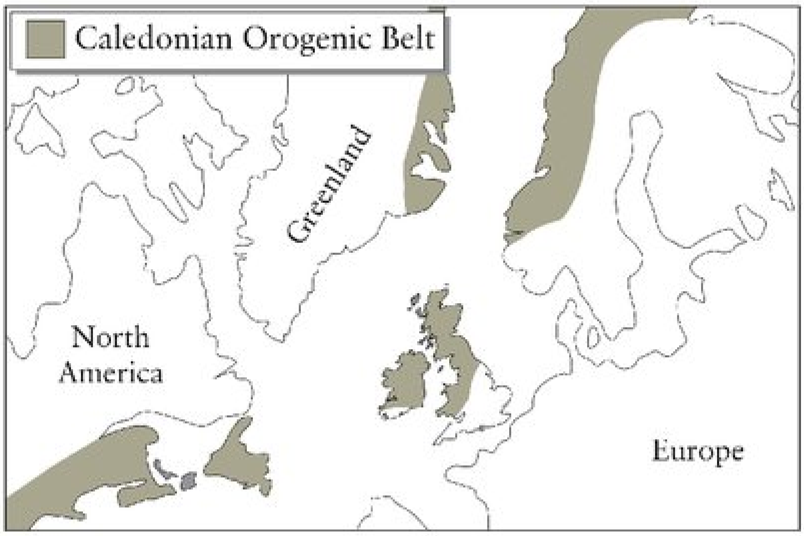


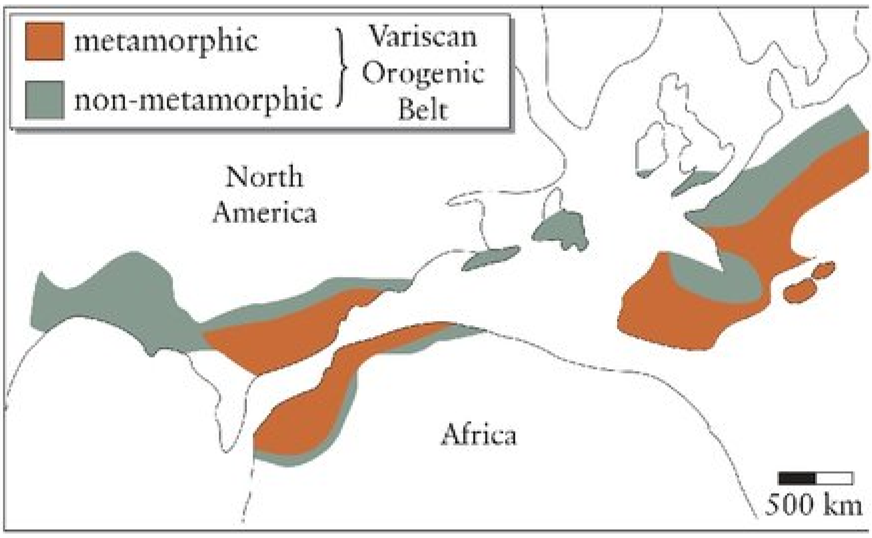
(Figure 14) The geological structure of south-east England, showing major topographic features associated with the Wealden Anticline, and the London Basin (syncline). Note that the Hastings Beds, Weald Clay, Lower Greensand, Gault Clay and Chalk comprise the Cretaceous shown on (Figure 13). After Edmunds (1983).

(Figure 15) The areas of higher ground in Britain. Nearly all of these are coincident with the relics of past mountain chains (compare with (Figure 16)). After Wilson (1994).

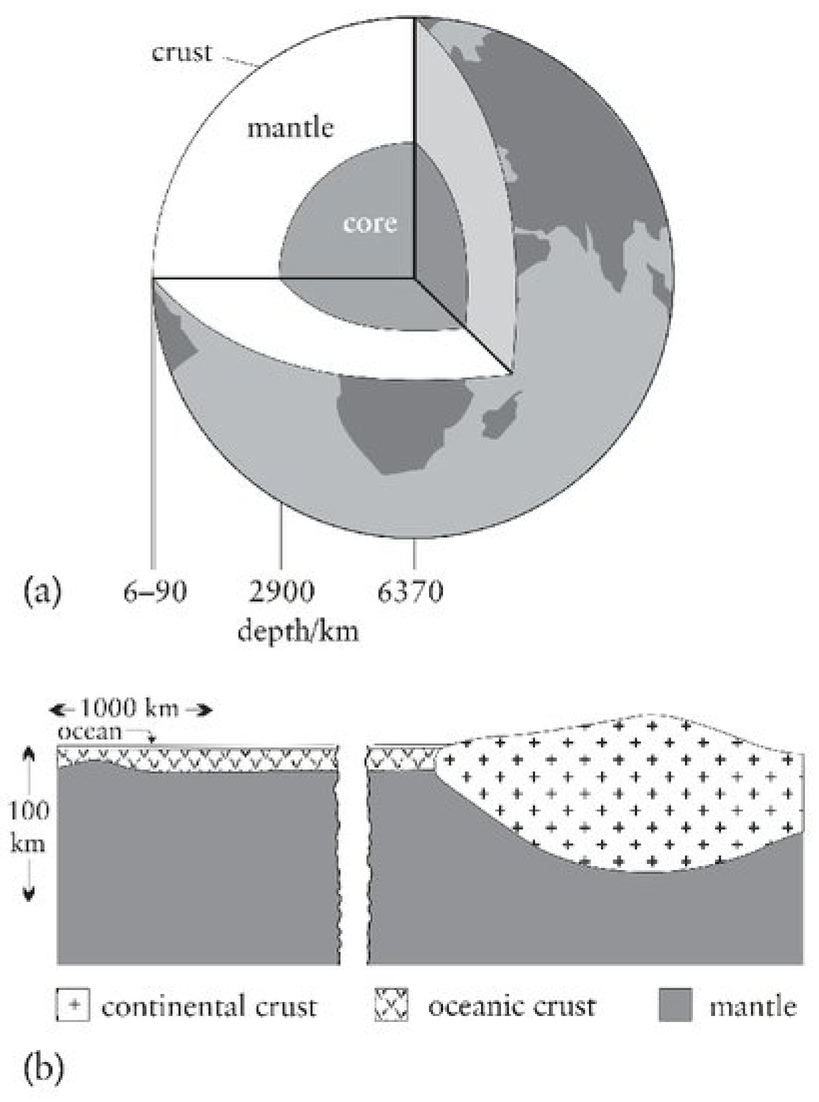


(Figure 16) British mountain belts. (a) Map showing the distribution of the major ancient mountain belts of Britain. Faults are major planar structures across which rocks have been displaced vertically or laterally. For example, the area in Scotland between the Highland Boundary Fault and the Southern Uplands Faults has been displaced downwards between the two faults, whereas lateral displacement occurred along the Great Glen Fault. (b) Chart summarising the ages of mountain building events and igneous activity. After Dunning et al. (1978).

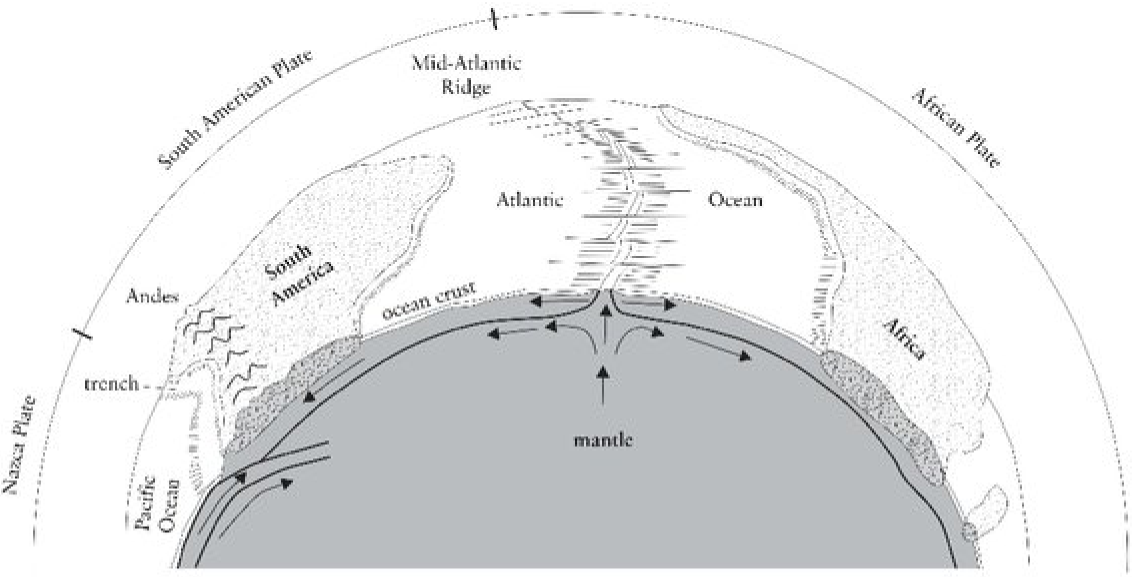




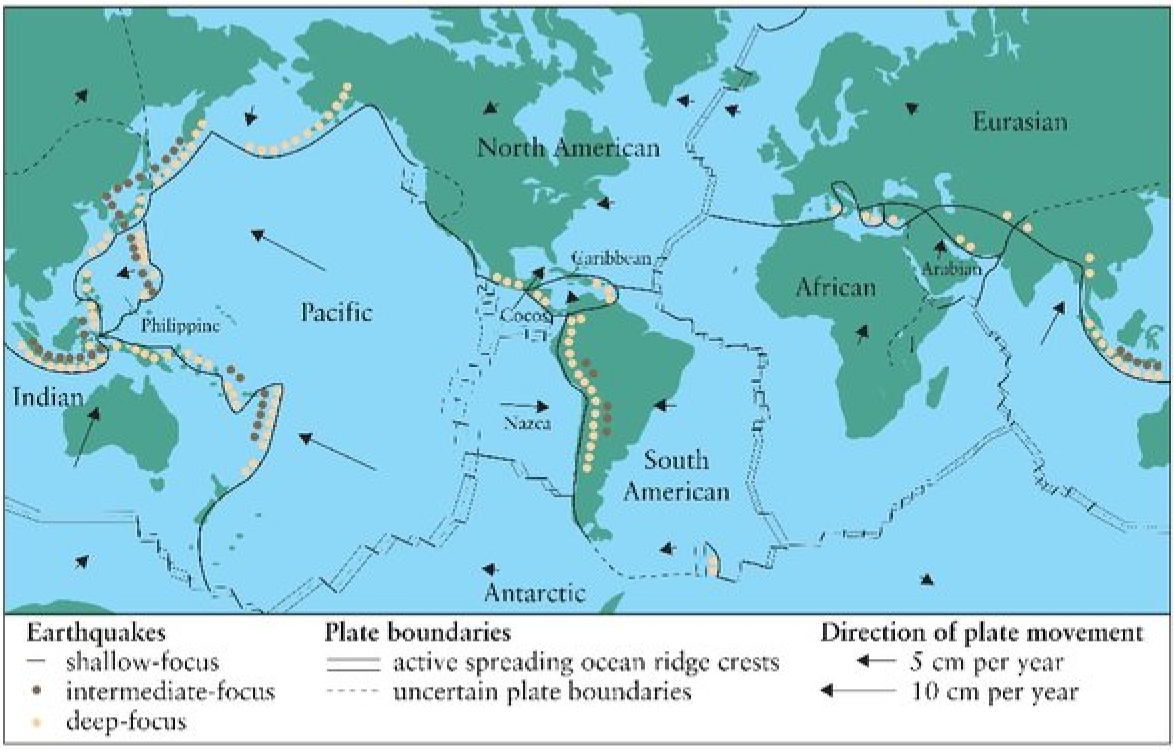
(Figure 17) The distribution of the Caledonian and Variscan mountain belts on a map of the continents reassembled to the positions they occupied before the opening of the present-day Atlantic Ocean. Early protagonists of continental drift used reconstructions such as these as evidence in favour of the former unity of now widely separated continents. After Wilson (1994).



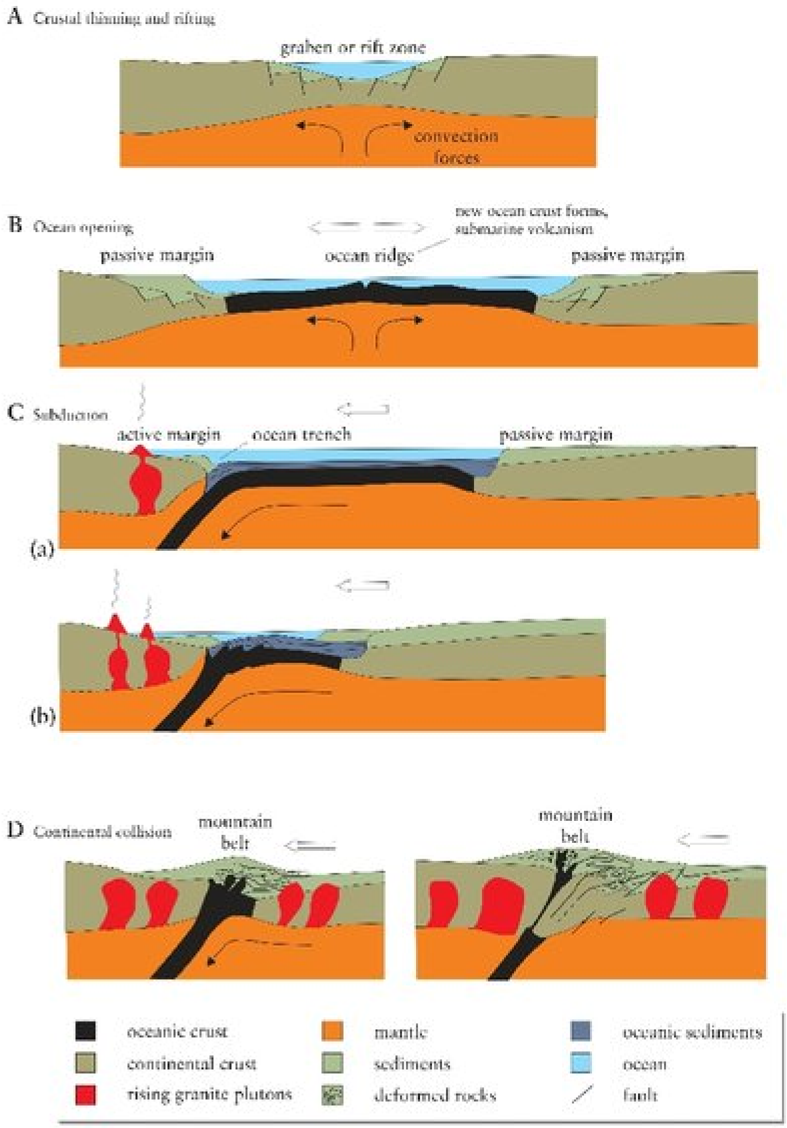
(Figure 18) The structure of the Earth. (a) Diagrammatic section through the Earth showing the core, mantle and crust. The crust is too thin to show to scale on this diagram: variations in its thickness are depicted in (b), a generalised section through the Earth's crust showing variations in the thickness of continental and oceanic crust. Oceanic crust is between 2.8 and 2.9 times denser than water, and is similar in composition to rocks such as basalt and gabbro; continental crust is less dense (2.6 to 2.8 times as dense as water), with a composition similar to granite. Continental crust is less dense and much thicker than oceanic crust, so it floats higher on the mantle. After Wilson (1994).



(Figure 19) The relationships of three crustal plates in the Earth's southern hemisphere. The thickness of the crustal layers is not to scale. New oceanic crust is constantly forming along the Mid-Atlantic Ridge. After Wyllie (1976).



(Figure 20) The present distribution of crustal plates and the earthquake activity at their boundaries. All the constructive plate boundaries are regions of shallow earthquakes, whereas deeper-focus earthquake zones mark the location of destructive plate boundaries. The rates at which ocean crust is forming at constructive plate boundaries are shown schematically by the width between the parallel lines used to depict them. The directions of plate movement are shown by arrows, the lengths of which are proportional to the rate of movement: the shorter the arrow, the slower the plate is moving. After Gass et al. (1972).



(Figure 21) Sequence of events in a cycle of ocean opening and closing, culminating in continental collision. It is possible for both plate margins to be subjected to subduction (as happened during the Caledonian mountain building in Britain), although this is not shown here.

(Figure 29) Sully Island, South Wales. Triassic rocks (230–195 million years old) were formed when 'Britain' lay within the arid belt north of the equator. They lie horizontally on the dipping Carboniferous Limestone. This angular discordance is known as an unconformity, and represents a period of several million years when there was no sediment accumulation. The rocks above the unconformity comprise sands and breccias which are interpreted as lake shore deposits. This site is one of the few places in the world where the margin of a former Triassic lake can be studied. Diagram after Wilson (1994). Photo: C.D. Prosser.

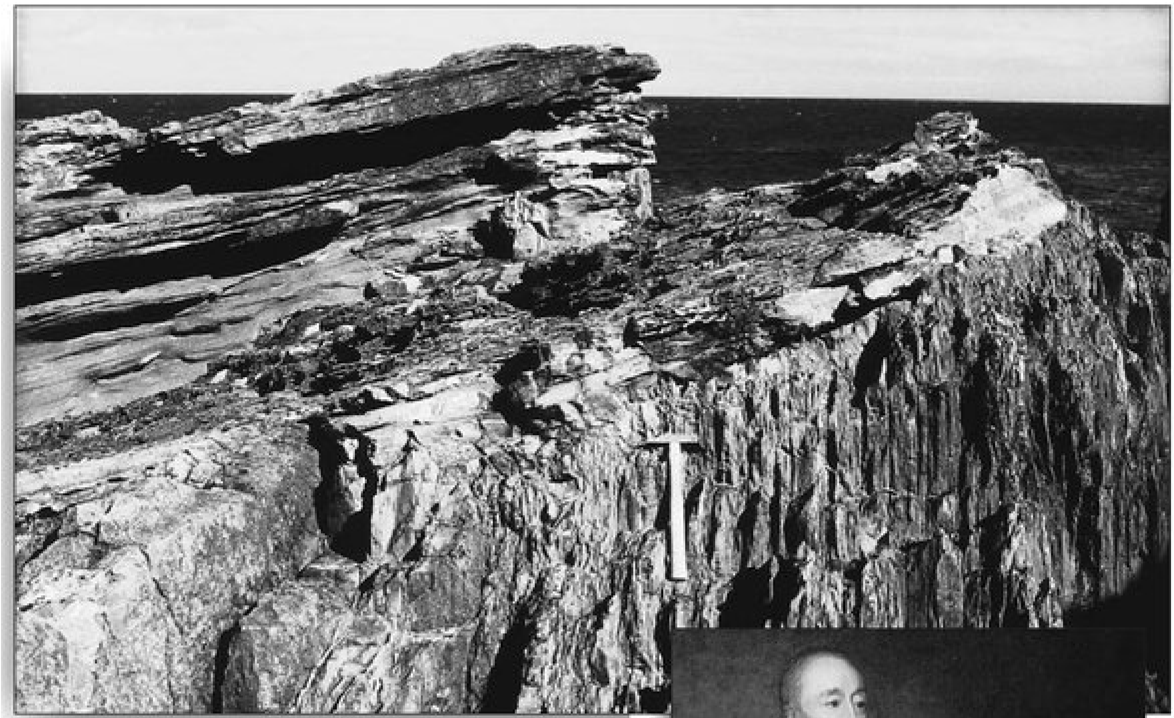


Figure 37. *Hutton's Unconformity at Siccar Point, Berwickshire, is one of the most famous and important geological localities in the world. The section at Siccar Point shows upturned Silurian sediments overlain by sediments from the Old Red Sandstone. The unconformity surface which separates these two sets of rocks represents a significant break in the continuity of the geological record. The portrait of James Hutton by Sir Henry Raeburn (detail) is reproduced by permission of the Scottish National Portrait Gallery. Photograph reproduced by permission of the Director, British Geological Survey. NERC copyright reserved.*

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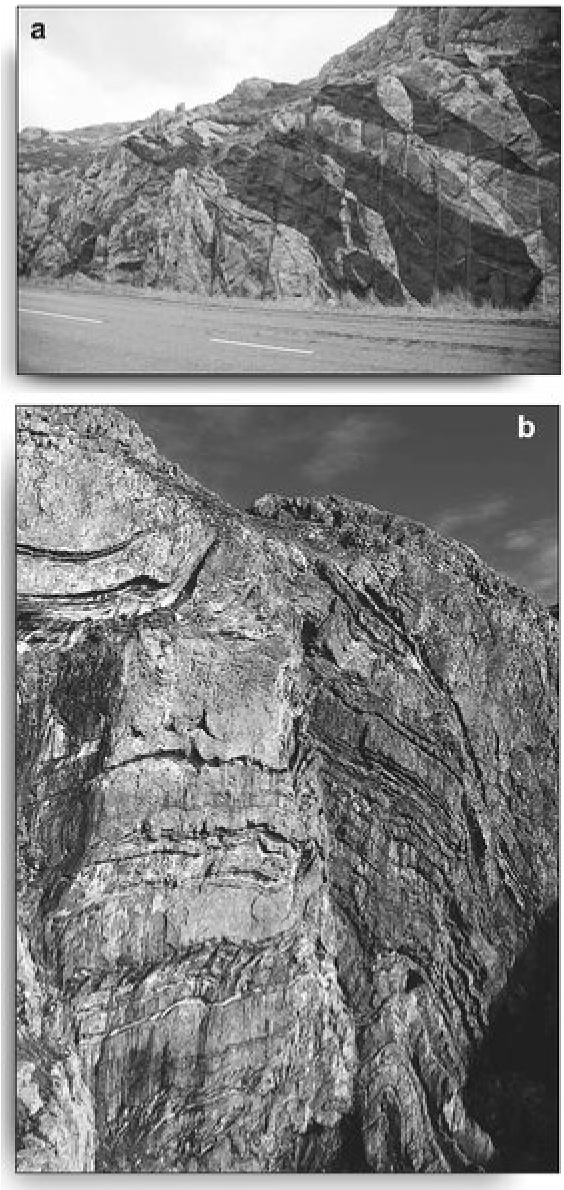
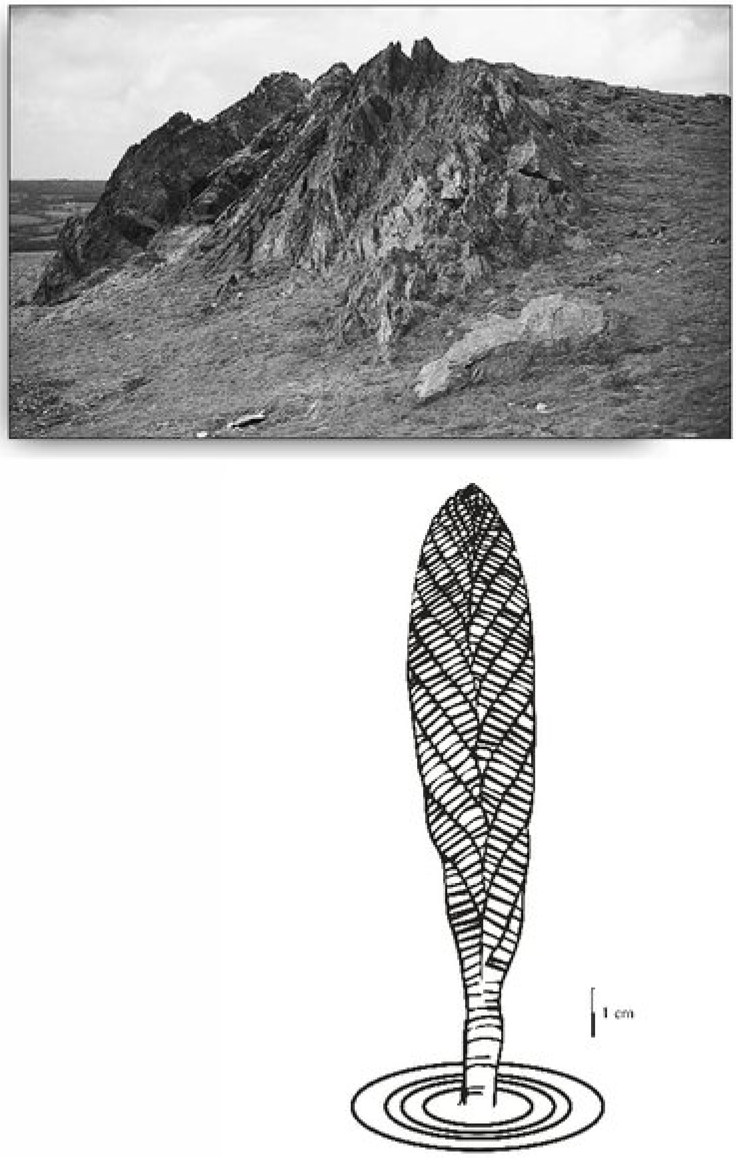
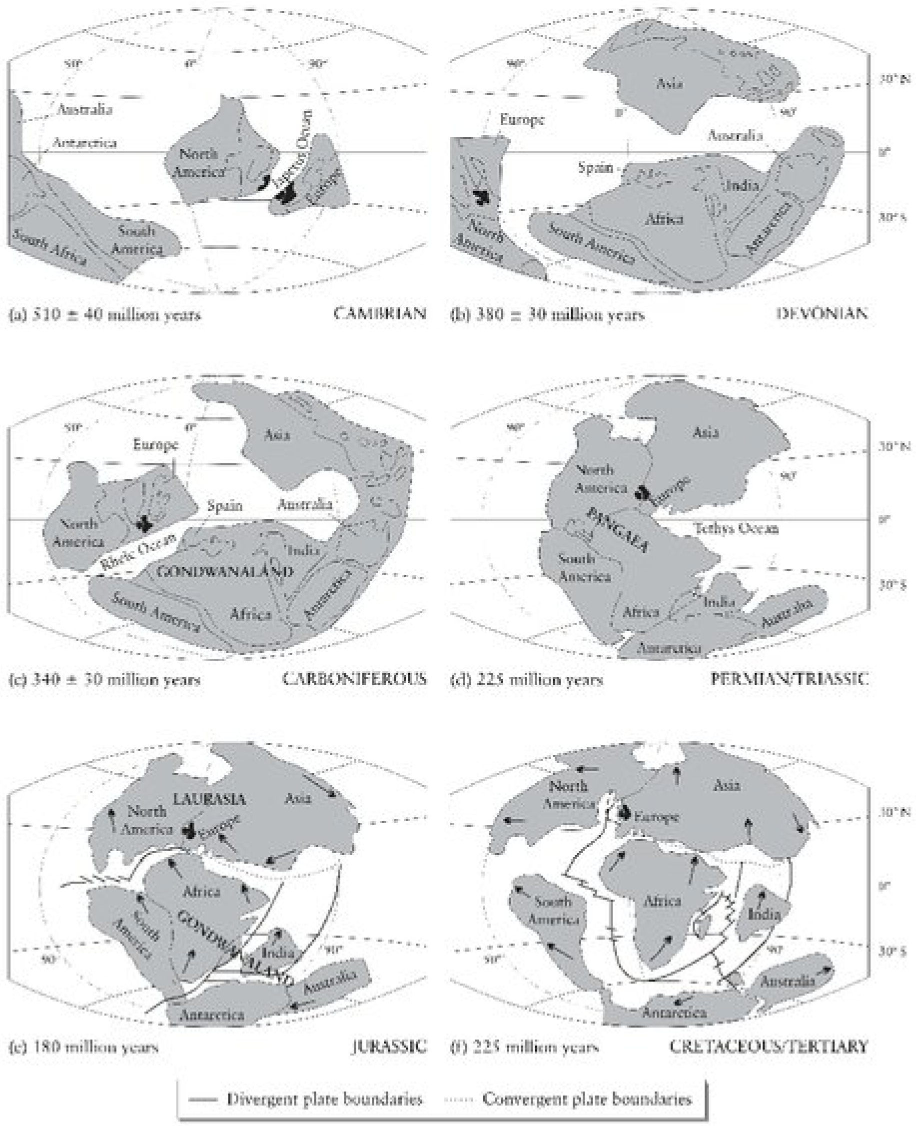


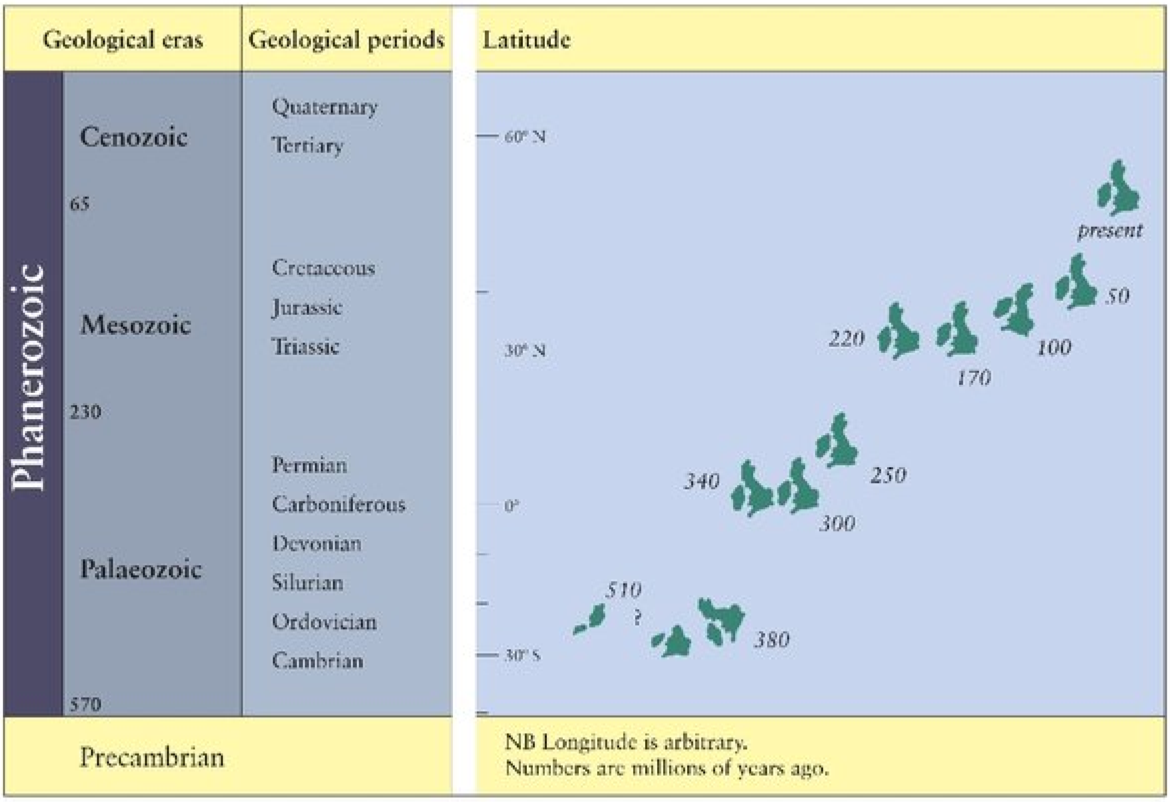
(Figure 22) Precambrian rocks. (a) The oldest-known rocks in Britain: the Lewisian Gneiss, in the north-west Highlands of Scotland. Some of these rocks were formed about 3,300 million years ago, in the Precambrian Era. Photo: R. Threadgould. (b) The Precambrian-age rocks at South Stack, Angelsey were deformed more than once. Photo: S. Campbell.



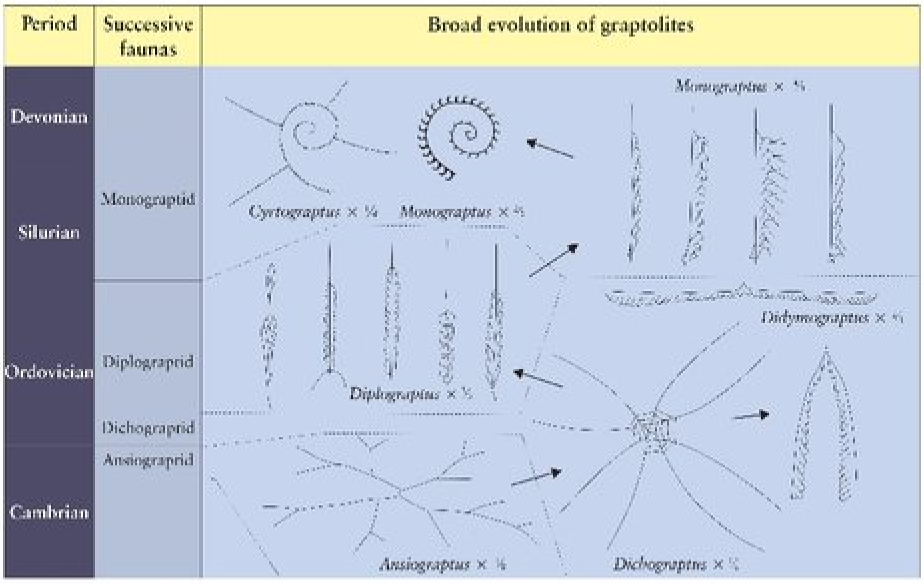
(Figure 3) The rocks of the Memorial Crags at Bradgate Park, Charnwood Forest, Leicestershire and reconstruction of Charnia masoni, a primitive life-form. The rocks exposed in the crags are probably 650–700 million years old. Occasionally, the rock surfaces show impressions of some of the first forms of life — imprints of soft bodies of some of the earliest large multi-celled organisms. These include the remains of jellyfish and sea-pen-like animals, including Charnia masoni. The preservation of soft-bodied animals is rare because they usually decay very soon after death or are eaten by scavengers. In this case, the animals were probably engulfed by a catastrophic event, perhaps the mass slumping of sediment, which trapped the fauna. The animals became preserved in the sediment, which eventually became rock. Because of the worldwide rarity of the preservation of these early life-forms, Bradgate Park is of great importance to the study of early life. Photo Leicestershire Museums.

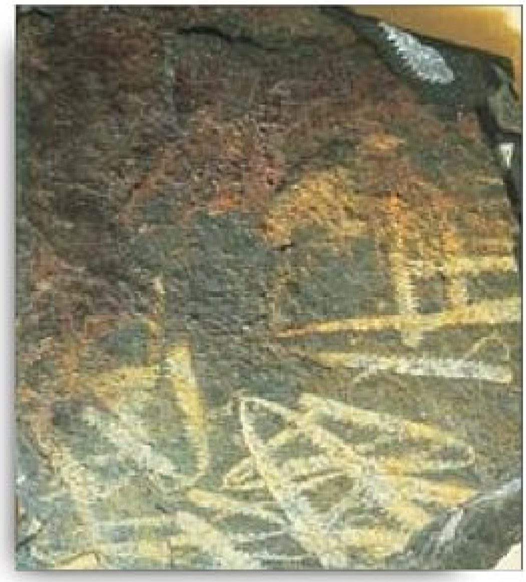


(Figure 23) Continental drift. Simplified maps illustrating how the continents were distributed during Earth history, indicating the locations of the different parts (dark shading) which have come together to form present-day Britain. After Wyllie (1976).



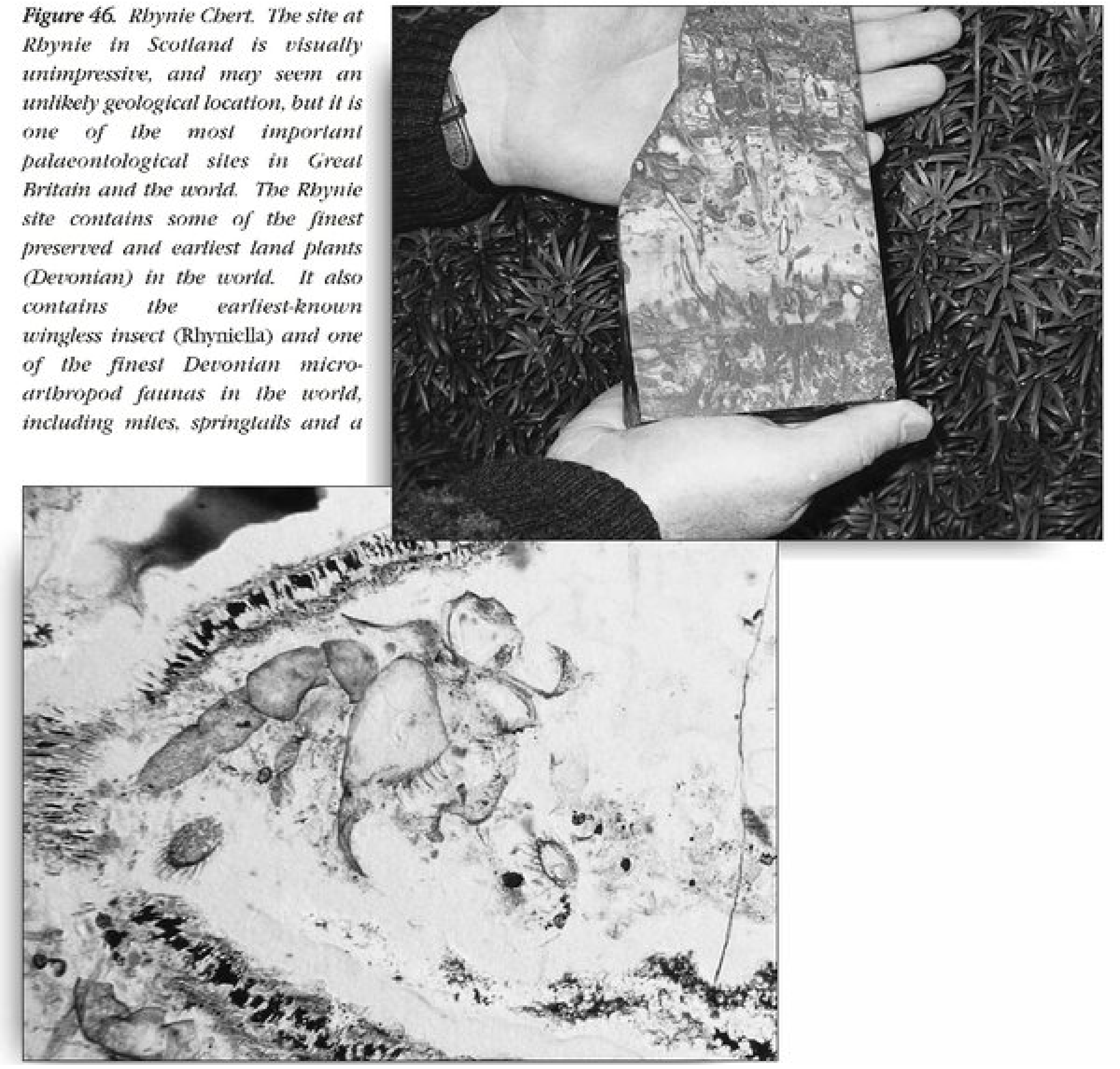
(Figure 24) The changing latitude of Britain through geological time. After Lovell (1977).



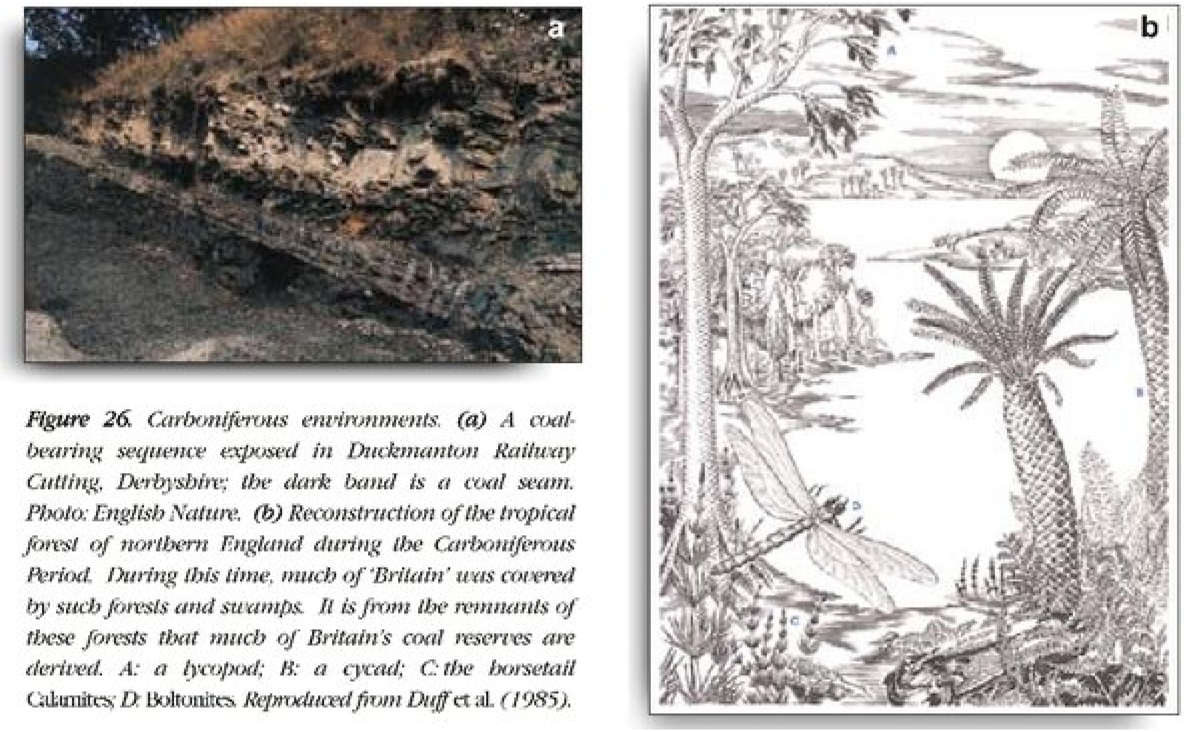


(Figure 39) Graptolites first become significant in the geological record in the early Ordovician Period, and became extinct in late Carboniferous/early Permian times. They were colonial organisms living near the sea-surface, consisting of one or more branches (stipes). The individuals of the colony lived in cups along the stipe. Their evolutionary development, as seen in fossils, led to the definition of the Ordovician Period. The photograph shows the graptolite Didymograptus murchisoni, from Dyfed, from rocks which are Llanvirn in age (between 455 and 470 million years ago). Photo: G. Larwood. Diagram after Rickards (1993).

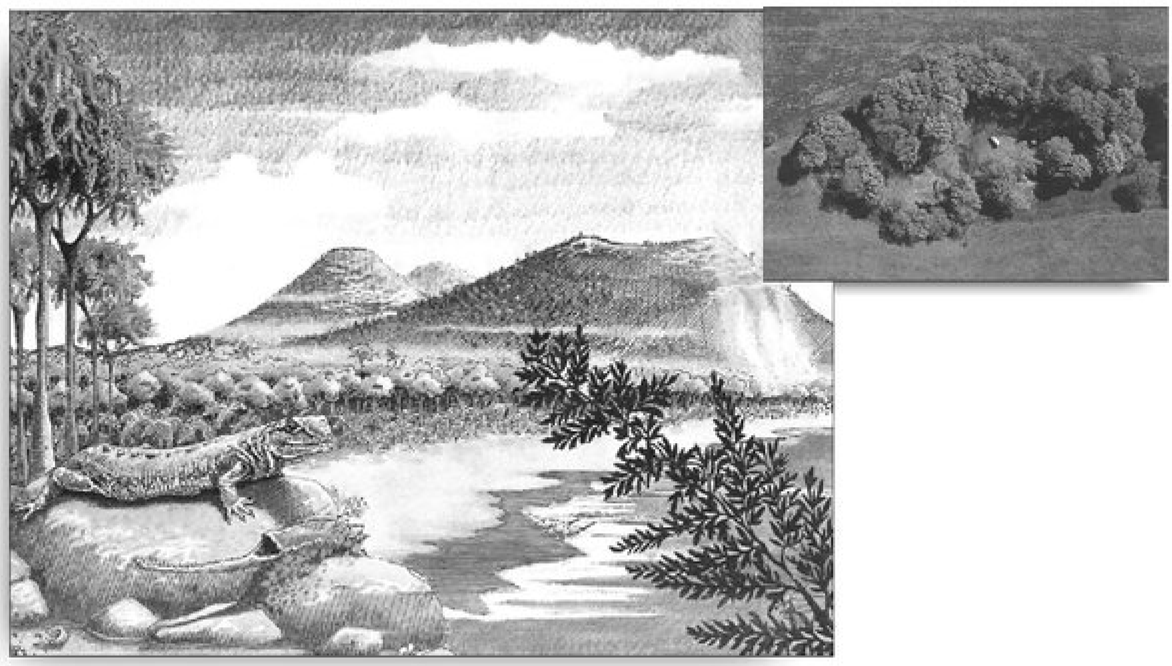
(Figure 25) Typical Lake District scenery in the Borrowdale Volcanic Group. The succession of rocks between the Langdale Pikes and Silver Howe represent a six kilometre thickness of volcanic lava and ash, erupted over a period of ten million years during the Ordovician Period. Photo: F.W. Dunning.



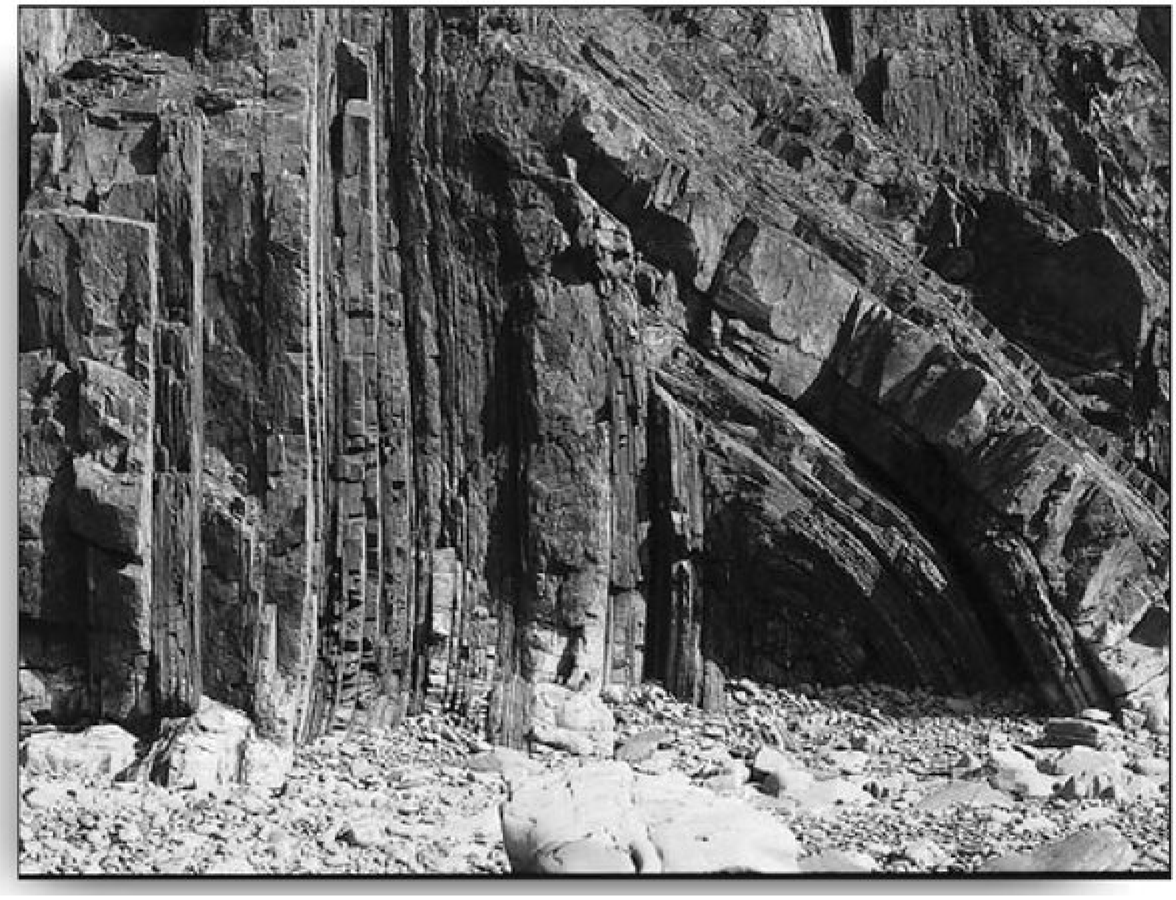
(Figure 46) Rhynie Chert. The site at Rhynie in Scotland is visually unimpressive, and may seem an unlikely geological location, but it is one of the most important palaeontological sites in Great Britain and the world. The Rhynie site contains some of the finest preserved and earliest land plants (Devonian) in the world. It also contains the earliest-known wingless insect (Rhyniella) and one of the finest Devonian micro-arthropod faunas in the world, including mites, springtails and a small aquatic shrimp-like organism, Lepidocaris. The fossils are preserved in chert. The deposit is an excellent example of the freak preservation of life resulting from the flooding of a marsh surface on which these plants were growing, by silica-rich water originating from a hot spring. The hot water killed and preserved the plants and animals before their tissues decayed, and so preserved a complete ecosystem. The arthropods found in the deposit are all primitive forms, and show an early association between plants and their parasites. Preservation is so good that microscopic damage to the plants by these arthropods is seen, as are invading fungal hyphae. The plants are preserved so well that thin sections of rock can be sliced, and examined under a microscope, to reveal the cell structure, including the minute detail of spores as well as cell xylem and stomata. The photographs show a sample and thin section of the chert. The thin section shows the mouthparts of a palaeocharinid (a spider-like arthropod). Photos: C.C.J. MacFadyen (chert sample) and N.H. Trewin (thin section).



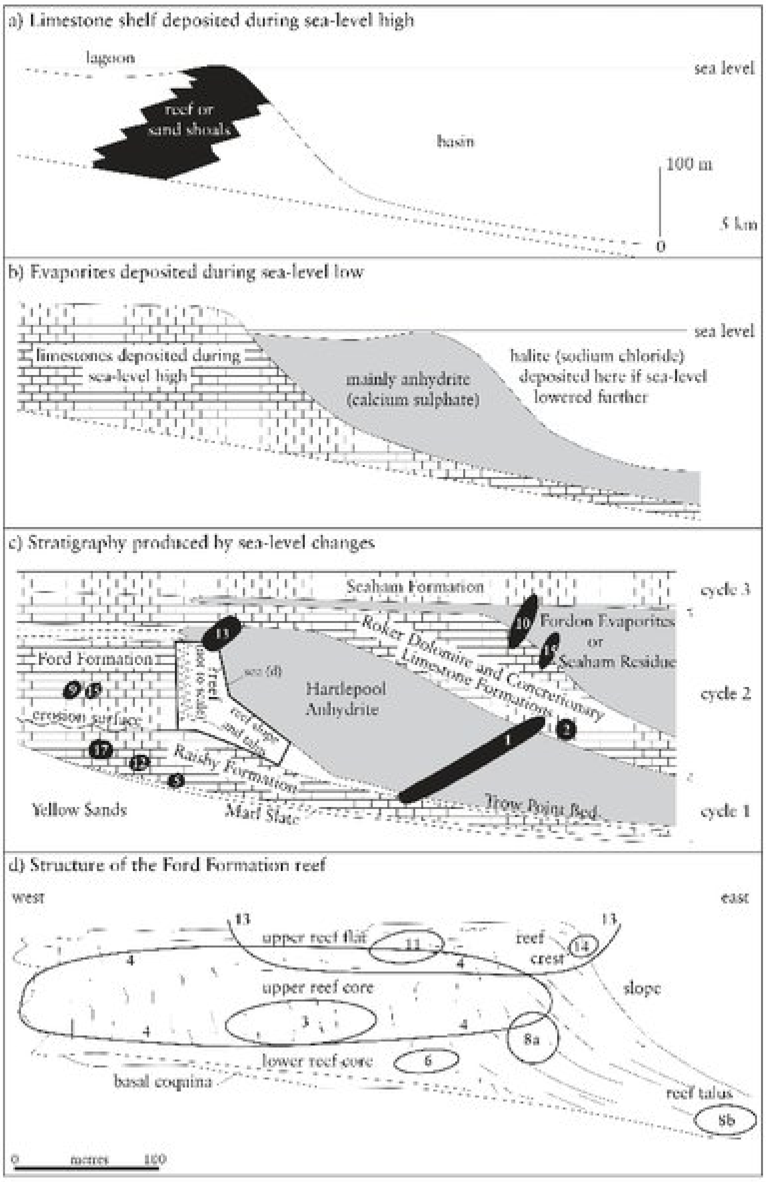
(Figure 26) Carboniferous environments. (a) A coal-bearing sequence exposed in Duckmanton Railway Cutting, Derbyshire; the dark band is a coal seam. Photo: English Nature. (b) Reconstruction of the tropical forest of northern England during the Carboniferous Period. During this time, much of 'Britain' was covered by such forests and swamps. It is from the remnants of these forests that much of Britain's coal reserves are derived. A: a lycopod; B: a cycad; C: the horsetail Calamites; D: Boltonites. Reproduced from Duff et al. (1985).



(Figure 27) East Kirkton, Lothian, Scotland: amphibians and a possible first reptile (shown in the left foreground). The limestone and shale exposures here, which are of Lower Carboniferous age, are very rich in fossils. The site is a disused limestone quarry. The quarry was abandoned in the middle of the last century and its palaeontological significance has been realised only recently. The nature of the limestone and its restricted distribution (600 metres across and less than ten metres thick) indicates that it may have accumulated in an area of hot springs caused by volcanic activity. It has yielded important early invertebrate and vertebrate faunas, including the earliest-known harvest spiders, millipedes, scorpions, the oldest complete amphibians and the earliest known reptile, Westlothiana lizziae, nicknamed 'Lizzie'. Reconstruction © M.I. Coates. First published in Clarkson et al. (1994). Photo: P.A. MacDonald.

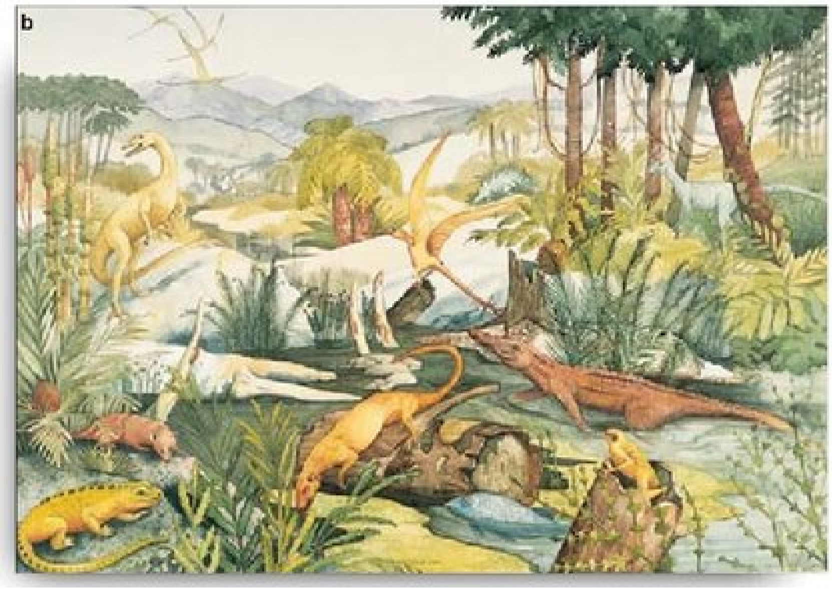


(Figure 28) Hartland Point, Devon. These Upper Carboniferous-age rocks were contorted into tight folds, by the Variscan Orogeny. Photo: A.R. Bennett.



(Figure 48) Rises and falls of the Zechstein Sea and the resultant rock succession in County Durham. (a) Deposition of limestone shelves, fringed by reefs, occurred during relative sea-level highs. (b) When the relative sea level dropped, the inland sea was probably partially cut off from the open ocean to the north, so that evaporation raised its salinity resulting in the deposition of evaporite minerals. (c) West to east cross-section showing the distribution of the dolomitised limestone and evaporite formations (and their residues resulting from near-surface dissolution). Cycles 1–3 shown on the right side of the diagram relate to the successive periods of high and low sea level depicted in (a) and (b) which resulted in dolomitised limestone formations being overlain by evaporite formations. The Yellow Sands shown at the base of the diagram were deposited from migrating desert dunes (similar sands in the southern North Sea are important gas reservoirs). The Marl Slate is a shale rich in organic material that was deposited immediately after the Zechstein Sea flooded the North Sea area. The numbers indicate the stratigraphical position of sites listed in the table on page 56. (d) Section showing the structure of the reef within the Ford Formation in Cycle 1. Numbers refer to sites listed in the table.

Figure 30. Jurassic environments. (a) Plesiosaurs from the early Jurassic based on specimens collected in Gloucestershire which are now housed in Gloucester City Museum. (b) Scene from mid-Jurassic times, showing a small lake surrounded by seed ferns and conifers based on the fossils from Hornsleasow Quarry, Gloucestershire. Fish (Lepidotus) live in the water, and frogs are present at the lake sides. Dinosaurs include some of the earliest stegosaurs and maniraptorans, plated and small carnivorous dinosaurs respectively. A carcass of a large sauropod dinosaur, Cetiosaurus, is rotting in the water, and Megalosaurus scavenges. Lizard-like animals, crocodiles, pterosaurs, mammals and mammal-like reptiles complete the scene. Paintings by Pam Baldaro. Reproduced by permission of the University of Bristol.



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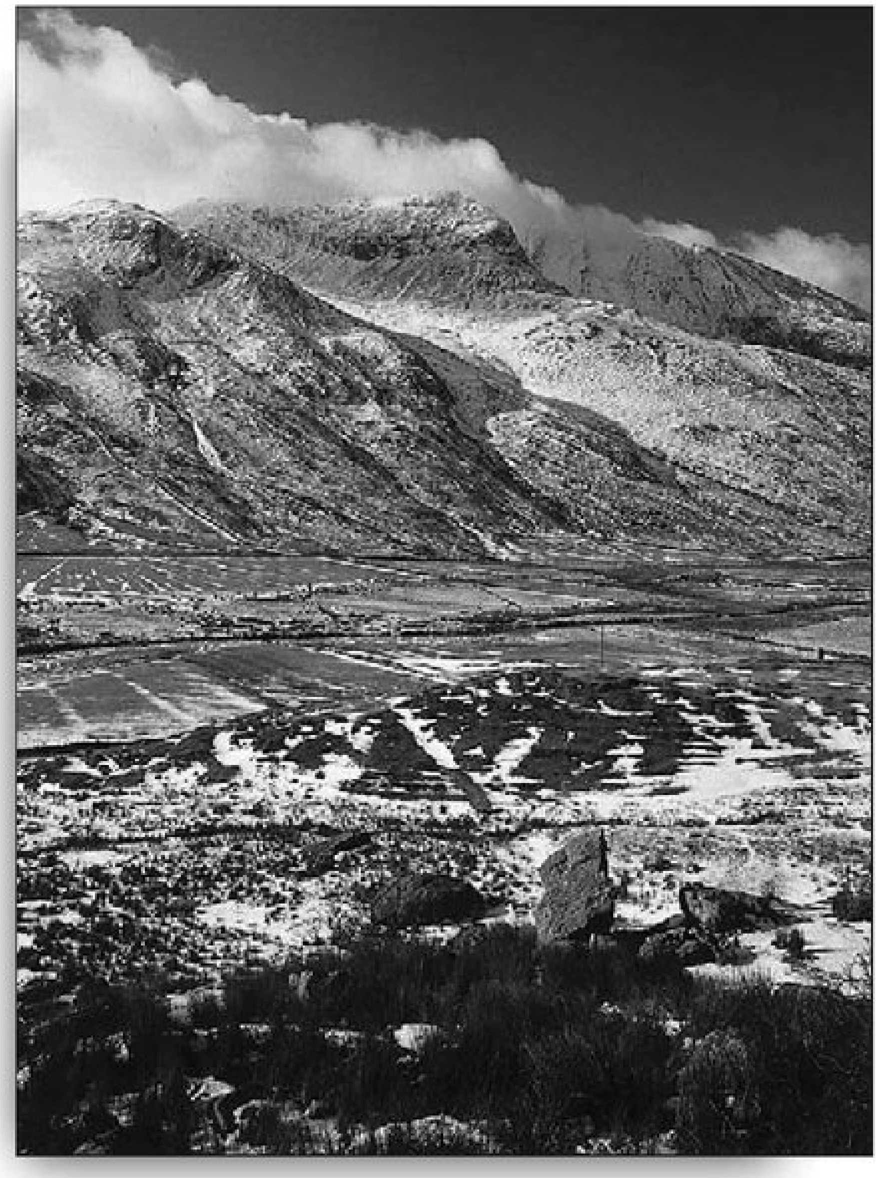
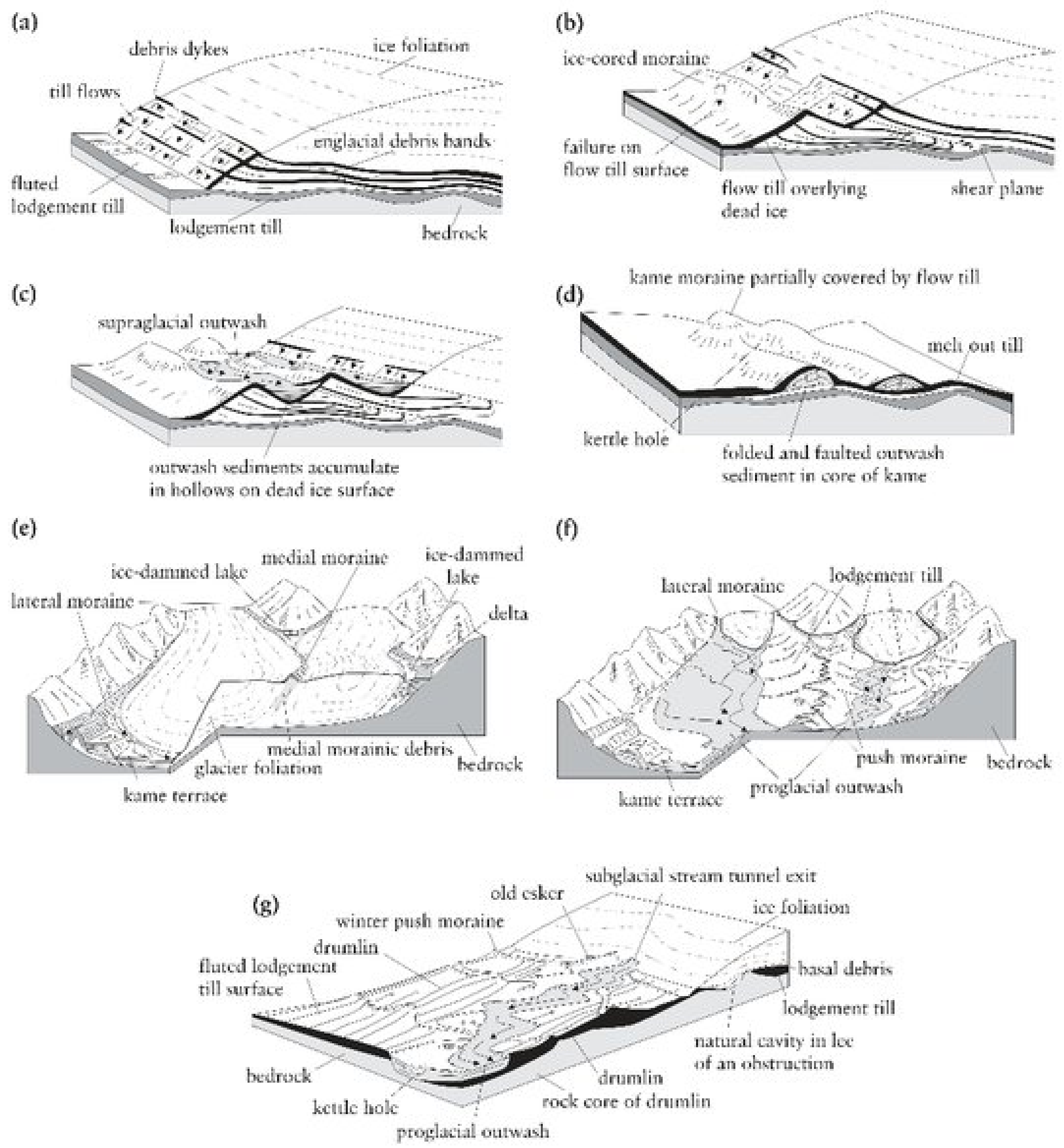
(Figure 31) The Seven Sisters chalk cliffs in East Sussex. The geomorphology of the cliffs is the result of marine erosion into a series of valleys and intervening ridges. Photo: N.F. Glasser.

(Figure 32) The Storr, Skye. The photograph shows the landslipped masses of basalt of the Skye Main Lava Series which occupy the foreground. Beyond the Old Man of Storr pinnacle, further lava flows of the Series form left-to-right-dipping scarps. Photo: David Noton Photography.

(Figure 33) Ice margins of British glaciations. The ages of these ice advances are: Loch Lomond Advance, 11,600 to 12,800 years ago Late Devensian glaciations ('the last glaciation'), 23,000 years ago Early Devensian Glaciation, about 60,000 years ago Ridgacre Glaciation (West Midlands), 160,000 years ago Anglian Glaciation, 450,000 years ago Bristol–Scilly Islands Glaciation, about 640,000 years ago.

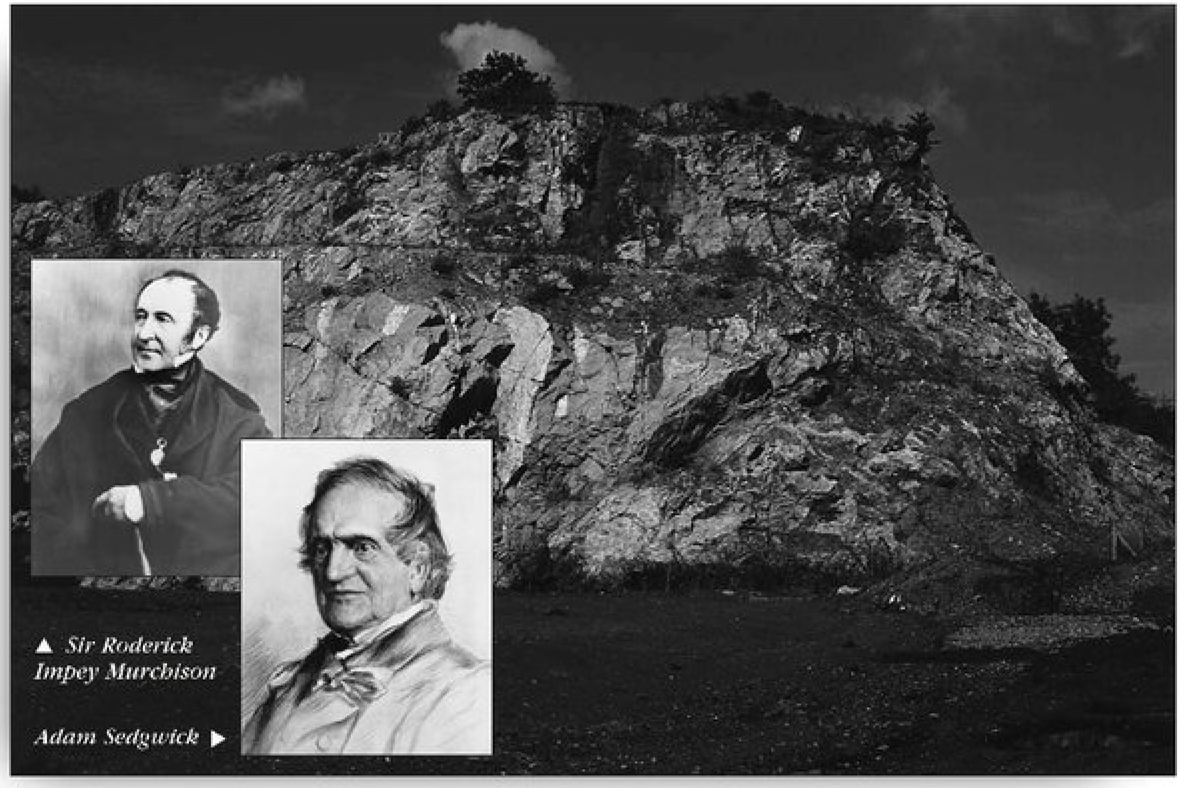


(Figure 34) Upland glaciation, Snowdonia, Wales. The photograph shows a series of cirques. A cirque is an armchair-shaped hollow, with a steep rock wall at the rear, and a lip or threshold at the front. The rock head wall is fashioned first by weathering and rockfall processes, whereas the floor of the basin is eroded and moulded by glaciers which occupied the hollow. Where two cirques meet, a precipitous divide called an arête develops (to the right in the photograph). Photo: S. Campbell.



(Figure 35) Schematic diagrams showing the formation of glacial depositional landforms and deposits. (a) Flow tills form on the surface of the retreating glacier from thick sequences of englacial debris. (b) Till cover inhibits melting of underlying ice which is left behind during glacier retreat as an ice-cored moraine ridge. Supraglacial flow till is still active. (c) Outwash from the active glacier is forced to flow between ice-cored ridges and tills flow into the outwash systems. When the outwash dries up, the flow till forms a capping. (d) Dead ice melts, thus reversing the topography and leaving melt-out till in its place. The kame sediments show collapse structures. Such sequences are extremely common in lowland Britain. (e) and (f) Development of the features of a glaciated valley. The principal features are lateral and medial moraines and kame terraces. (g) The formation of the subglacial/proglacial sediment features. The till surface bears drumlins and on it are superimposed fluted moraine ridges; push-moraine ridges are associated with readvance of the glacier front, either in winter during a general retreat phase or in response to longer term cooling; lee-side till forms in a natural cavity where debris falls from the ice roof. Relatively rare eskers form in subglacial or englacial stream channels; proglacial outwash cuts through the till; kettle holes form in old outwash where stagnant ice blocks melt-out (the underlying sediments show collapse structures). A simple stratigraphy of outwash on till is produced by a single glacial episode of advance and retreat. After Boulton and Paul (1976).

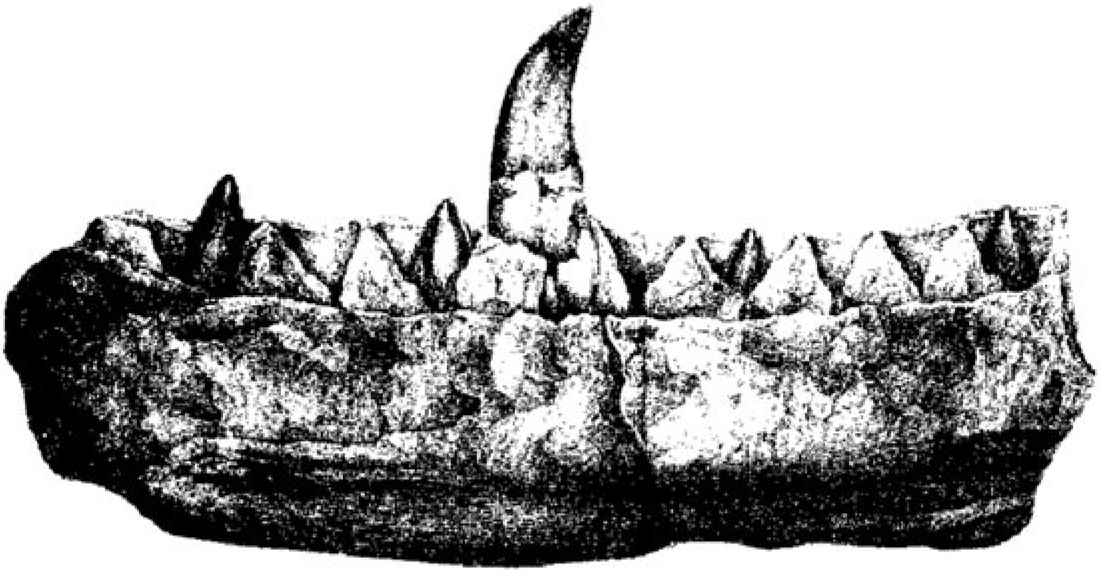
(Figure 36) West Runton, Norfolk. Sediments exposed in the cliff and on the foreshore accumulated during two interglacials and three ice ages. Fossil pollen indicating the presence of temperate forests has been obtained from the interglacial deposits, while the ice-age deposits show permafrost structures and subarctic herb floras. The dark band at the bottom of the cliff is the 'Freshwater Bed', deposited by a river. Photo: N.F. Glasser.



(Figure 38) Lummaton Hill Quarry Site of Special Scientific Interest, Torquay, Devon. The rocks exposed in the quarry are massive limestones which were deposited in the later part of the Middle Devonian Period (the Givetian Stage). The limestone contains shell-rich pockets seen here in the upper part of the face. This locality is of great historical importance because the rich faunas it has yielded were used, in part, to characterise the original Devonian System of the pioneering geologists Sedgwick and Murchison. Portraits reproduced with permission of the Director, British Geological Survey. NERC copyright reserved. Photo: K.N. Page.

Figure 40. *The Jurassic rocks of the cliffs near Lyme Regis and portrait of Mary Anning. Portrait reproduced by permission of The Natural History Museum, London. Photo: P. Doyle.*

(Figure 40) The Jurassic rocks of the cliffs near Lyme Regis and portrait of Mary Anning. Portrait reproduced by permission of The Natural History Museum, London. Photo: P. Doyle.



(Figure 43) Type specimen of Megalosaurus bucklandi Meyer, 1832. Partial lower jaw. Stonesfield is the most important of the British Bathonian localities in the Cotswolds, and arguably the best Middle Jurassic terrestrial reptile site in the world. Its fauna is diverse and abundant, and consists of more than 15 species of fossil reptile, including turtles, crocodilians, pterosaurs, dinosaurs and rare marine forms (ichthyosaurs, plesiosaurs), as well as mammal-like reptiles and mammals. Stonesfield is the most important site in the world for remains of Megalosaurus. It yielded the 'type' material in the early nineteenth century, and continued to produce hundreds of specimens while the mines were in operation. Diagram after Buckland (1824).